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AGARD CONFERENCE PROCEEDINGS 577

Flight Simulation — Where are the Challenges?

(Simulation de vol — quels sont les défis?)

Copies of papers presented at the Flight Vehicle Integration Panel Symposium, held in Braunschweig, Germany, from 22-25 May 1995.

NORTH ATLANTIC TREATY ORGANIZATION

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Organisation du Traité de l'Atlantique Nord

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Flight Simulation — Where are the Challenges?

(AGARD CP-577)

Executive Summary

Effective flight simulation is an important capability for NATO nations, and it will become even more important in the face of reductions in defence budgets. The principal objectives of this symposium were to review the state of the art in flight simulation, and to identify key areas where additional research and development are needed. Presentations dealt with simulation used for engineering and for training, both on the ground and in flight.

The symposium met its objectives. The papers contained in the Proceedings should be valuable to anyone currently:

— considering the implications of procuring and applying simulators;

— developing simulators for training and engineering;

— using simulators for engineering;

— doing basic research in simulation.

The Keynote speech, by Major General G.K. Muellner, USAF, provided a dramatic stimulus to the symposium by describing how advanced modelling and simulation methods are being used in the Joint Advanced Strike Technology (JAST) programme to achieve an affordable weapon system.

Technical papers in the symposium deal with visual and motion cueing, advances in modelling, simulation in design and development for both rotorcraft and fixed wing aircraft and their systems, simulation in training, in-flight simulation, and the future applications of networked simulators. Many of the papers were based on current military programmes: Eurocopter Tiger, Comanche, Osprey, Rafale and the C-160, and included the use of piloted simulation in the evaluation process of bids for an attack helicopter.

A significant theme emerged, to use simulators linked up via networking technology to expand the scope of man-in-the-loop simulation into battlefield environments using a mixture of simulated and real mission equipment. Cost savings in development have been achieved as a result.

Weaknesses in current flight simulation technology were identified in the area of visual displays, in particular in achieving wider fields of view and higher resolution; in ground handling models; and in verification and validation. A new approach to identifying and defining the features required in simulated visual scenes was outlined; it would be useful to extend this new approach by further research in NATO nations. There is still considerable debate on how much motion the pilot needs to 'feel', and in what circumstances. This may well lead to a future study project in the Flight Vehicle Integration Panel.

The most interesting trend apparent throughout the symposium, from the Keynote onwards, was the concept that future simulators should be designed and procured for a wide spectrum of uses. A simulator created to design air-to-air missiles should also be used to test missiles, and it should be suitable for integration into a training system. It is even conceived, for example, that a simulator testing infra-red suppression systems in France could be flown against a simulator developing heat-seeking missiles in Canada, as part of a distributed simulation network exercise testing NATO's air C31. Such multi-echelon usage will reduce costs and improve the realism of the synthetic environment being simulated.

Simulation de vol — quels sont les défis?
(AGARD CP-577)

Synthèse

La compétence en matière de simulation du vol est d'une grande importance pour l'ensemble des pays membres de l'OTAN et le deviendra de plus en plus eu égard à la réduction généralisée des budgets de défense. Ce symposium a fait le point de l'état de l'art dans le domaine de la simulation du vol, afin d'identifier d'éventuels points faibles pour lesquels un effort supplémentaire de recherche et développement serait nécessaire. Les présentations ont porté sur la simulation pour ingéniérie et pour l'entraînement, tant au sol qu'en vol.

Le symposium a atteint ses objectifs. Les communications figurant dans le compte-rendu de conférence doivent intéresser tous ceux qui:

— envisagent l'achat et la mise en œuvre de simulateurs

— travaillent au développement de simulateurs pour l'entraînement et l'ingéniérie

— utilisent des simulateurs aux fins de l'ingéniérie

Le discours d'ouverture, prononcé par le Major-General G.K. Muellner USAF, a été un stimulant opportun pour le symposium, notamment par la description de l'application de méthodes avancées de modélisation et de simulation dans le cadre du Programme conjoint des technologies de frappe avancées (JAST), qui a pour objet la fabrication d'un système d'armes abordable.

Les communications techniques du symposium ont porté sur la stimulation visuelle et motrice, les derniers progrès en modélisation, la simulation dans la conception et le développement d'aéronefs à voilure fixe et à voilure tournante et de leurs systèmes, la simulation et l'entraînement, la simulation en vol et les applications futures des simulateurs en réseau. Bon nombre des communications, structurées autour de programmes militaires actuellement en cours (Eurocopter Tiger, Comanche, Osprey, Rafale et C-160), traitaient de l'emploi de la simulation pilotée lors du dépouillement des soumissions relatives à un hélicoptère d'attaque.

Le symposium a identifié le thème important de l'utilisation de simulateurs reliés entre eux par les techniques de réseaux, afin d'élargir le champ de simulation de «l'homme dans le boucle» dans les environnements du champ de bataille, par l'association d'équipements opérationnels réels et simulés. Il en est résulté des économies de coûts de développement.

Un certain nombre de lacunes ont été identifiées dans le domaine des technologies de la simulation du vol, en particulier en ce qui concerne les visualisations, où il s'agit d'obtenir des champs de vision plus larges et une meilleure résolution, les modèles des manœuvres au sol, la vérification et la validation. Une nouvelle approche du problème de l'identification et la définition des caractéristiques topographiques demandées pour la simulation de séquences visuelles a été exposée. Le symposium a considéré que ce sujet devait faire l'objet de nouveaux programmes de recherche à réaliser par les pays membres de l'OTAN.

Il existe toujours un débat important sur la question de la quantité de mouvement qui doit être perçue par le pilote et, dans quelles circonstances? L'intérêt exprimé pour ce sujet pourrait se concrétiser sous la forme d'un projet d'étude pour le Panel FVP.

La tendance la plus intéressante, qui s'est manifestée tout au long du symposium, du discours d'ouverture jusqu'à la fin, a été la notion de la conception et l'achat des futurs simulateurs offrant une large gamme d'applications. Un simulateur étudié pour la conception de missiles air-air devra aussi servir pour les essais et devra être intégrable dans un programme d'entraînement. Il est même envisagé, par exemple, qu'un simulateur d'essais d'un système de suppression infrarouge développé en France puisse être comparé à un autre au Canada travaillant sur le développement de missiles à autodirecteur infrarouge dans le cadre d'un exercice de simulation d'un réseau réparti pour les essais des moyens C3i air de l'OTAN. De telles applications multi-échelon permettront de réduire les coûts et d'améliorer le réalisme de l'environnement synthétique simulé.

Contents

Preface

Effective Flight Simulation is an important capability for NATO nations, and it will become even more important in the face of reductions in defence budgets. This symposium reviewed the state of the art in flight simulation, in order to identify weaknesses where additional research and development are needed. Presentations dealt with simulation used for engineering and for training, both on the ground and in flight.

Papers on fixed and rotary wing, as well as tilt-rotor, aircraft are included. Much of the material was oriented on military applications: Eurocopter, Comanche, Osprey, Rafale, and the C-160. Simulation was addressed both for individual systems and for distributive networks.

Acknowledgements

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1. INTRODUCTION

Flight simulation continues to be an area of expanding applications and technical growth. This has been driven to a considerable extent by demonstrated cost benefits that accrue from its use. Many of the papers presented at this symposium touched upon military cost savings associated with simulator use. In addition, increasingly groups of simulators are being networked together in order to expand their application into large-scale military operations in order to study in a cost effective manner an expanding repertoire of battle scenarios.

The AGARD symposium "Flight Simulation — Where Are the Challenges?" addressed a wide range of topics covering the development and application of flight simulators. Most of the papers either directly dealt with military topics or could be applied to military aspects of flight simulation.

The symposium, held in Braunschweig, Germany, from May 22-25, 1995, was divided into the following seven sessions: Visual and motion cueing and requirements, Advances in modelling, Simulation in design and development — rotorcraft, Simulation in design and development — fixed wing and systems, Simulation in training, In-flight simulation: its uses and benefits, and Future applications.

2. PRELIMINARY SPEAKERS

Keynote Speaker: MGen G. K. Muellner
The keynote speech was provided by Major General G. K. Muellner of the United States Air Force, who has had an illustrious career in military flight and was well qualified to lead off the symposium. His challenge to the audience was based on his experience as Program Director of the Joint Advanced Strike Technology Program (JAST). This program is focussed on developing the next generation strike aircraft weapon system for the US Navy, Marine Corps, Air Force and now the UK Royal Navy. He outlined his vision for achieving an affordable weapon system through the effective application of modelling and simulation, which he described as "the dominant factor" in achieving the program's goals. His vision was based on four key areas. First, use modelling and simulation to support joint government and industry studies of possible trade-offs between cost and performance, and thus define an affordable requirement. Second, expand the role of simulation in the design and development process accomplishing as much as possible in the virtual world before building hardware, creating software or planning assembly. Third, use expensive flight and ground tests only as validation points for results obtained through modelling and simulation. Fourth, design all models, databases and simulation tools to be re-usable at all stages of the system's life cycle, including evaluation, training and force deployment. He illustrated this vision by describing how the JAST program, in what is truly a dramatic expansion of the role of modelling and simulation, is exploiting these concepts to achieve effectiveness, supportability and, above all, affordability.

Setting the Scene: S. B. Anderson
This presentation was intended to set the scene for the symposium by giving an historical perspective based on the speaker's extensive flight simulation experience at NASA Ames Research Center over the years. By viewing the challenges and solutions from the past perhaps we will get a clearer picture of where we are currently headed. Flight simulation at Ames began in the late 1940's and has progressed over the years to the current version of the vertical motion simulator (VMS) and the in-flight simulation using a UH-60A Black Hawk helicopter. A very complete chronicle was presented along with the lessons learned at each stage. For example, they found that it was possible to obtain useful answers to problems from even crude simulators. The speaker passed on a number of suggestions gained from experience:

(1) the task often dictates the level of motion fidelity required.
(2) vertical motion should not be compromised.
(3) visuals with a wide field-of-view are often needed.
(4) in-flight tests will often be needed to accurately define flight criteria.
(5) understanding the human element of the system is an important challenge.

3. SYMPOSIUM ORGANIZATION

The symposium was divided into seven sessions containing 34 technical papers. It was concluded with a round-table forum which addressed the questions "What challenges have been identified?" and "What issues for the future have emerged?"

The general layout of the symposium was as follows:

Session I — "Visual and Motion Cueing and Requirements." This topic is central to the flight simulation field. Because it is a very broad subject area the papers in this session could only hope to touch upon a few current points of interest. This was done with the emphasis on visual scene content requirements and display resolution. Some of the latest thinking on motion systems rounded out the session.

Session II — "Advances in Modelling." Three of these papers related to helicopter modelling with an emphasis on helicopter/ship interface simulation. One paper dealt with the nagging problem of modelling aircraft ground handling. The final paper touched on modelling the tactical environment.

Session III — "Simulation in Design and Development - Rotorcraft." The first paper in this session dealt with the fairly new concept of employing simulations of candidate helicopters in the aircraft selection process. Two papers dealt with the application of simulators in the development of tilt-rotor aircraft. To round out the session, the use of simulation in the design of more conventional helicopters was described.

Session IV — "Simulation in Design and Development - Fixed Wing and Systems." This session contained a collection of papers spanning a broad range of simulator applications. These included aircraft development, HUD symbology development, a multi-target simulator, flight clearance of vehicle management systems and a description of the NLR simulation facility. Although all the papers were interesting, the session lacked cohesion.

Session V(a) — " Simulation in Training." This session began with a detailed description of the German experience with the Tornado low level training simulator. This was followed by two very useful papers on the structuring and analysis of training programs. The final paper dealt with pilot response to wind shear on the landing approach as measured in flight simulator studies. This highlighted an unexplained tendency for pilots to respond late to the onset of wind shear effects.

Session V(b) — "In-flight Simulation - Its Uses and Benefits." This was a very cohesive session with all the major players in the in-flight simulator business represented. The papers tended to be up-to-date descriptions of the various facilities. Some examples of the application of in-flight simulation were included to demonstrate the capability of such devices. An interesting addition to this session was an informal report, during the general discussion period, on Russian in-flight simulation over the years.

Session VI - "Future Applications." The papers in this session tended to emphasize networking of simulators and a simulation environment that goes beyond the flight simulator itself. One paper on mobile training simulators pointed the way towards smaller, low-cost trainers in the future.

The total participation at the symposium was indicative of a successful meeting with 152 in attendance, of whom 46 were authors, 40 panel members and 66 observers. The complete range of simulation community members was represented and formal papers from six nations were presented.

4. TECHNICAL EVALUATION

Session I — Visual and Motion Cueing and Requirements

The first paper of this session was a tutorial on visual information. This was followed logically by a practical paper on how to develop a visual data base. The next paper fitted in nicely by describing the on-site evaluation of several simulator visual systems. The next two papers dealt with the application and design of simulator motion systems. The final two papers were descriptions of recently developed image generation systems.

The tutorial presented in **Paper 2** began by cautioning the visual data base designer to be careful when deleting objects because we cannot presently predict which ones are necessary for a specific task. The paper then went on to list the common features of static and dynamic scenes. The authors then dealt with simulator hardware considerations and pointed out that it was not possible at the present time to optimize the visual display system's performance in all areas simultaneously. A special discussion was dedicated to the simulation of rotary wing vehicles. The paper ended with the challenge to make improvements through a list of research and development topics. Although the authors did not deal with the potential benefits of helmet-mounted displays, they presented an excellent overview.

Paper 3 described the development and application of a technique for identifying what features should be presented in simulated visual scenes for helicopter battlefield operations. The first step in the process is to identify and prioritize flying activities in the battlefield. Next, the relative importance of visual scene components must be determined. Finally a relational database is generated that can be used by scene designers when selecting objects to include. A practical process for carrying out these steps was developed and described in the paper. The authors carried out field trials to demonstrate the process and then implemented simulator trials. The process was deemed to be successful. The authors concluded their paper with seven challenges to advance their work to the next level of understanding. The paper was quite complete and covered a broad range of work.

The following presentation (**Paper 4**) was unique in that it reported on the evaluation of simulator visual displays by the user community, that is, operational fighter pilots. Three different visual display technologies were covered: projector/dome, rear projection faceted, and fiber optic helmet-mounted display. They employed 26 tactical tasks in a subjective evaluation of training effectiveness. They found that all the visual systems could be used to train some but not all of the evaluation tasks. They concluded that current systems do not provide adequate contrast, resolution and brightness to allow for air model discrimination.

The motion cueing experiment described in **Paper 5** was well conceived and executed. Its purpose was to determine whether the yawing motion channel was necessary in helicopter simulators. The experiment took place in the NASA Ames VMS configured as an AH-64 helicopter. The tasks involved both small and large yaw amplitudes under four different motion constraints. Minimal motion washout was employed. The conclusion of the experiment was that the yaw rotational motion degree-of-freedom may not be necessary in the simulation of hovering flight. This fact can then be used to free up extra travel in other degrees-of-freedom in such motion systems as the popular hexapod configuration.

The analysis of the motion system hydraulic actuator loop described in **Paper 6** was intended to show how modern control designs can be combined with modern actuators to minimize time delay and increase bandwidth. Although no reasoned case was made proving that this step is essential to cure an identified flaw in current simulators, it does make sense to do the best you can when building a state-of-the-art research simulator. We can look forward to its demonstrated effectiveness when the new simulator is completed.

Paper 7 described a new image generator product employing advanced Z-buffer technology (AZtec) for hidden surface elimination and anti-aliasing. This process speeds up image processing by eliminating the need to process transparent faces at the end of each computation cycle. A general description of the APOGEE image generator was given in rather broad terms.

The Real-Time Simulation System (RTSS) as developed within the European ESPRIT project HAMLET was outlined in **Paper 8**. From the description it would appear that this image generator is similar in performance to current low end hardware. Its strong feature is expandability and thus it may find applications where this is essential.

Session II — Advances in Modelling

In this session the first two presentations dealt with the simulation of helicopters landing on small ships. The next paper dealt with turbulent inputs to simulator rotor models and thus could be tied in with the first two papers. This was followed by a description of the development of a ground handling model. The final paper in this session dealt with generating friendly and enemy aircraft in the simulation of a tactical environment.

Paper 9 tackled one aspect of the simulation of

helicopters landing on small ships. The helipad being at the stern of these ships is subject to the ship airwake created by the upwind hull and superstructure. This effect must be created in the simulator because it impacts directly on the pilot's ability to operate his helicopter while over the deck. A modular airwake model has been developed based largely on published data and models describing wind effects around buildings. The model is modular in form and includes: corner flow, lee rotor flow, profile drag flow, and inflow/outflow. A suitable turbulence model has not yet been developed. The resulting model has been tested against wind tunnel data and tested in the Advanced Flight Simulator at DRA Bedford. In the latter case pilot acceptance was favourable. The authors suggested that further improvements will be made shortly. This model shows great promise.

The next presentation (**Paper 10**) covered the broad spectrum of topics related to simulating the operation of helicopters from small ships. The previous paper's airwake work was included as one item of interest. The author expanded on the needs involving visual cues, motion cues, the aircraft mathematical model, the ship airwake and turbulence representation, and ship motion modelling. Tying in with the Session I material, it was pointed out that in the visual display area there is a need for good scene texturing and high resolution, while good motion cues (including realistic heave cues) can lead to more realistic workloads for the pilot. Some example results from simulation projects involving handling quality ratings and performance were presented. This work has indicated that the ADS-33 Level 1/Level 2 boundaries need to be modified for helicopter/ship operations. The paper ends with a list of challenges for future developments. Overall, the paper indicated a very active and effective program in this area.

The problem of generating turbulence inputs for helicopter rotor models was addressed in **Paper 11**. Here the problem was to develop a technique that could be implemented in real-time and still produce results acceptable to the simulator pilot. The proposed technique is called Simulation of Rotor Blade Element Turbulence (SORBET) and it was tested on the blade element rotor model found in the helicopter code GenHel. Tests demonstrated that current articulated and semi-rigid rotors are insensitive to in-plane turbulence and hence only the vertical component need be generated. SORBET generates two independent turbulence fields located at two points upwind of the rotor. Filtered white noise (using the Dryden spectrum) is employed and it is spread along a line between the points (the onset line) using a process called Gaussian interpolation. The frozen flow assumption is then applied, allowing the turbulent field to sweep over the rotor. When flown in the VMS in a UH-60A simulation, pilots responded favourably.

Paper 12 outlined the generation of a ground handling model for a simulation of the C-160 transport aircraft. The process included physical modelling and actual taxi trials. A parameter identification process was used as part of the development (but not described in detail). Of interest was the use of an impulse input to simulate the complex spin-up of the wheels on landing. No mention was made of how the model handled holding with brakes against engine thrust. Overall, the process described appears to reflect current practice in this area.

The last paper in this session (**Paper 13**) differed from the rest in that it described the computer generation of friendly aircraft and enemy aircraft in a battle simulation scenario. The author discussed the requirements, the algorithm and the technology needed to implement this approach to generating a tactical environment. He concluded by noting that it was very difficult to completely remove human intervention from this process.

Session III — Simulation in Design and Development - Rotorcraft

The first paper of this session described the use of flight simulation as part of the evaluation process in the procurement of an attack helicopter. The next two presentations dealt with the contribution of flight simulation to the development of tilt-rotor aircraft (the third paper also included the RAH-66 helicopter). The final paper in this session involved the use of flight simulation in the development of an attack helicopter.

The use of piloted flight simulators to evaluate proposed aircraft during the procurement decision-making process is a fairly new concept. **Paper 14** described the UK experience in applying this technique to three candidate attack helicopters. The required helicopter data were supplied by the bidders and the simulation was carried out in the Advanced Flight Simulator configured with a Lynx cockpit. Handling qualities and agility were assessed by the evaluation pilots following ADS-33. The pilots were pleased with the process and the results. The paper concluded with a summary of important simulator features needed for

this kind of work. The process described in this paper appears to be effective and likely to become the standard means for evaluating aircraft during procurement. As noted by the audience, once an aircraft has been accepted through this process it will be up to the manufacturer to prove that the aircraft (when finally built) meets the performance of the simulator.

Paper 15 - withdrawn.

Paper 16 described the use of the NASA Ames VMS facility in a study of design requirements related to a commercial tilt-rotor transport aircraft. Five piloted simulator experiments were carried out aimed at cockpit design questions and terminal area operations (both normal and emergency). Sample results were provided of handling qualities results. As part of the project the authors also considered airport facilities designs directed at tilt-rotor operations.

Both the V-22 tilt-rotor and the RAH-66 helicopter were involved in the work described in **Paper 17**. The authors indicated that both constructive simulation (off-line) and virtual simulation (piloted, ground-based) played a significant role in the development phases. Of note was the fact that (following the new trend indicated in several symposium papers) in the V-22 program a triple lab tie in link was established among: (1) the flight control laboratory, (2) the flight simulator laboratory, and (3) the mission computer/avionics software laboratory. It was found that this resulted in fewer flight tests and lower overall costs. The authors see a strong future for distributed interactive simulation and virtual prototyping.

Paper 18 documented the use of flight simulation by EUROCOPTER in developing their helicopters over the past ten years. Their SPHERE simulator is being used in the development of the NH-90 helicopter. They also employ simulators to study handling qualities and the man/machine interface.

Session IV — Simulation in Design and Development - Fixed Wing and Systems

To some extent this session became a catch-all for a number of papers on diverse topics. The first two papers described the authors' experiences in employing simulation during the development of fighter aircraft. The next paper concerned the design of HUD symbology for aggressive 3-D maneuvers. Paper 22 discussed vehicle management systems with some reference to simulation. Paper 23 was a facility description of the Dutch National Simulation Facility, and the last paper was a description of an air-to-air weapon system simulator.

The authors of **Paper 19** described their experiences using fixed-base flight simulators during the design and development of the AMX (air-to-ground mission) and the EF2000 (air-to-air mission). This type of paper can be very useful to an audience of simulator people because we can all learn from others' experiences. The authors described some of the problems encountered and how they solved them (just as the author of Paper 1 did). For example, attempts to simulate refueling failed due to the absence of motion cues and a stereoscopic display.

Paper 20 outlined the use of flight simulation during the Rafale development. An important aspect of this program was the controlling of costs. The paper presented the background of the simulation and test program carried out to obtain defence approval of the aircraft configuration. The program represented a successful cooperation between government and industry.

The problems associated with the generation of HUD symbology during aggressive maneuvers was the genesis of **Paper 21**. In particular the pitch and roll attitude symbology used on conventional HUD's is difficult to interpret under these conditions. The authors described an Arc Segment Attitude Reference (ASAR) symbology that eliminates this problem. The concept was first demonstrated during simulator trials in 1987. The paper traced the development of the ASAR to the final version established in 1994. The paper demonstrated a very successful interplay between simulator tests and flight tests in developing new display technology.

The author of **Paper 22** presented an excellent tutorial on vehicle management system concepts. This included the concept of flight clearance. He also pointed out that in the future, simulation will play an important role in this process.

Paper 23 described the new Dutch National Simulation Facility (NSF). It is currently involved in the F-16 mid-life update program. Its capabilities will be extended to helicopter simulation later in 1995 to support work on the CH-47D and AH-64D.

Paper 24 outlined the architecture of a piloted multi-target simulator for air-to-air weapon system development. It is capable of generating many possible targets while creating a realistic operational tactical environment. There can be many piloted simulator stations on the net. It was found that pilots are more motivated when engaging a colleague rather than a computer-generated opponent. The system is DIS compatible.

Session V(a) — Simulation in Training

The first paper in this session was an excellent summary of the efforts made to create a simulator for low level fighter mission training. The next two presentations described the analysis and evaluation of simulator training programs. The final paper dealt with pilot response to windshear.

Paper 25 — withdrawn.

The German Air Force, under pressure from environmental considerations, initiated a program to replace live low level training by flight simulator training. This presentation (**Paper 26**) was a clear description of how they attempted to achieve this goal with an upgraded Tornado simulator. To the original simulator they added a six degrees-of-freedom motion system, a G seat, a G suit and a fiber optic helmet-mounted display system. During the evaluation phase both objective and subjective evaluations were carried out. Unfortunately the initial results were negative in that training effectiveness could not be proven despite the fact that the pilots were extremely impressed by the simulator. Before the system problems could be rectified the program was cancelled. This task is obviously very difficult to simulate but perhaps the problems could have been overcome if they had been allowed more time.

Paper 27 was a tutorial on how to structure a simulator-based training program. This is perhaps an area of expertise that is often not properly employed when we develop training devices. Some common training myths were clarified and many useful ideas were presented. The authors closed by reminding us that the objective of the training process is to produce a change in people. We must also ensure that the training objectives are clearly understood and achieved.

Perhaps one of the most important tasks in the training simulator environment is the assessment of training effectiveness. The author of **Paper 37** concentrated on combat mission training. He pointed out that most of this training is conducted at the operational unit. This, however, is becoming more difficult and expensive and they are looking to DIS as a partial solution. Training effectiveness can be assessed by: evaluating simulator fidelity, gathering subjective opinions, measuring within simulator performance improvement, and performing transfer of training studies. He describes the results from tests carried out at the unit level and results from applying the Multi-Service Distributed Training Testbed. It would appear that simulator networking has become an effective training tool.

Paper 28 described the use of two simulators to study pilot response to windshear during the landing approach. It was demonstrated that the display of pertinent data to the pilot could be used to eliminate a potentially fatal tendency on the part of pilots to delay (by about 30 seconds) the response necessary to successfully fly out of danger.

Session V(b) — In-Flight Simulation - Its Uses and Benefits

The four papers in this session represent the state-of-the-art of in-flight simulation. They were mainly facility descriptions although the third paper included a long sequence of brief descriptions of research carried out on their simulators. The session was rounded out by a description during the discussion period of in-flight simulation in Russia.

Paper 29 described a new Canadian facility called ASRA based on a Bell 412 HP helicopter. It will be converted to a fly-by-wire in-flight simulator in the near future. The presentation included a list of steps required for this conversion. For safety and performance, it has been decided to employ a two actuator compound actuator in each of the pitch and roll channels. The author has verified the performance of such a design through computer modelling of the system. By building on their past experience with their Bell 205 facility it appears that the new system with its increased agility will be a welcome addition to the in-flight simulator community.

The US-developed RASCAL is based on a modified UH-60 helicopter. **Paper 30** described the work in progress aimed at completing this facility. The presentation emphasized the helmet-mounted display and research flight control system aspects of this development. Its future application will be directed towards the development of integrated control, sensor

and display technology in order to increase the capability and safety for all-weather, low-level rotorcraft operations. As with the ASRA of Paper 29, the schedule has been arranged to allow the conduct of research programs during the development period. The presentation included lists of test programs to date, and subsystems to be included. This facility will incorporate several unique features that will make it an extremely capable research tool.

The German ATTAS and ATTHeS in-flight simulators have had a long history of research activity. **Paper 31** reviewed the main features of these facilities and briefly described several past research projects. The ATTAS (based on a VFW 614 aircraft) has been used for: flight controls development, reconfiguration following system damage, A3XX in-flight simulation, and small airliners controls refinement and flight envelope protection. ATTHeS (based on a BO 105 helicopter) has been used for: bandwidth criteria evaluation in support of ADS-33, rotor decoupling study, Lynx in-flight simulation, and vision-based hovering under adverse conditions. The facilities have made significant contributions in several areas.

Paper 32 described the US VISTA in-flight simulator based on AF-16D aircraft. They have just completed Phase II of their development, test and evaluation, and the authors reported on the test results. It was pointed out that in this time of shrinking budgets, the VISTA project depends on minimizing costs in order to survive. They plan to branch out into non-traditional missions such as acting as technology demonstrators and test beds. Efforts will also be made to find new customers (e.g., foreign civil organizations). It would appear that they have an excellent product and a progressive attitude which should bring success in the coming years.

Session VI — Future Applications

The first three papers of this final session dealt with distributed simulation topics with the second paper also describing a mobile flight simulator. The final paper discussed the concept of the synthetic environment, of which flight simulation is a part.

The author of **Paper 33** presented a discussion of how to implement distributed interactive simulation. He talked about problems of timing and how they could be solved. The point was made that how problems are handled is scenario-dependent. It would appear that there are still a number of difficulties to be overcome before DIS fully matures.

The presentation of **Paper 34** described the development of a mobile AH-1W aircrew procedures trainer. This appears to be a direct response to the generally stated goal of reduced costs. The system features: reduced physical size, COTS computers, and full-size system performance. The paper lists nine design requirements for the ideal Small Mobile Trainer. Technical details are given concerning the computer and the visual system. An aircraft-based system was then proposed as a further means of reducing costs. In this scenario a ground-based operational aircraft becomes the heart of the system, an idea that has proven useful in the past for research facilities.

Paper 35 was a survey on the topic of advanced distributed simulation (ADS). As a review, the presentation reiterated many of the topics brought out by previous speakers. For example, the trend towards the increasing use of system integration labs was pointed out. You can mix and match real and virtual players in an ADS environment to achieve cost savings. The author pointed out the differences in simulator requirements between test and training functions. The ADS challenges were listed along with the key related activities and developments. This was a good summary paper and was well-placed in the program.

The final **Paper 36** described a concept termed the Synthetic Environment. The author defined this to be "a computing based environment which allows the risk reduction of defence issues to take place through the interaction of people, models and live equipment". The levels in this structure range from "customer defined geopolitical scenarios" down through "simulations and live equipment" until reaching "systems support". Thus flight simulation is only one cog in the wheel. The flight simulation element would be used within a DIS protocol where it was noted that as the number of DIS participants increase, technical limitations (e.g., transmission bandwidth) cause the fidelity to decrease. The users of the synthetic environment would carry out: forces training and mission rehearsal, mission planning, and defence policy analysis. The message appears to be that we in flight simulation should be prepared to participate in much larger organizational structures than we have in the past.

Round-Table Forum

A lively exchange of ideas took place during the round-table forum held at the end of the symposium. Several

observations and topics brought out in discussions at the end of each session have been included below.

1. *The Trade-Off Between Motion and Visual Cues* — This is always a hot topic for discussion at any simulator conference and the present symposium was no exception. The discussion began with the statement that motion systems were too expensive and all that is really needed is a good visual display. This was countered by several rebuttals. In the end the consensus appeared to be that there are scenarios where motion is required and those where it is not.

2. *Visual System Development* — In this instance, the need for improved visual displays was expressed. The desire for resolution approaching eye limits, wide field-of-view, and full field-of-regard was expressed. The air-to-air trainer group felt that improved resolution was essential while scene content could be reduced. On the other hand, those involved in helicopter simulation felt that for the hovering task, increased scene content (microstructure) was needed. It was agreed that improving visual simulator cues would be a long term task. Ending on a positive note, the opinion was expressed that in the next five to seven years improved visuals might allow the simulation of 95% of all flying tasks.

3. *Simulation Use During Aircraft Development* — On this topic it was claimed that a good development simulator can save the cost of one development aircraft. In this era of reduced budgets this certainly appears attractive. For this to be fully exploited it was pointed out that there is a need to speed up the updating of simulator properties during aircraft development projects.

4. *Distributed Interactive Simulation* — Here the consensus was that DIS should be nourished by government support (as in the UK and US) and encouraged to grow.

5. *Fidelity* — It was pointed out that the required level of fidelity depends on the task under study. In addition more time should be devoted to improving the operational fidelity of our training facilities. In a related area, it was felt that more effort should be placed on verification and validation of simulators, including operations near the edges of the flight envelope.

6. *Additional Areas Requiring Further Development* — Here a number of areas were pinpointed. Ground handling is still in need of better models. As well, more work should be done on high angle-of-attack aerodynamic models, external loads, elasticity, air-to-air refueling and unusual flight attitudes.

7. *Russian In-Flight Simulators* — In an informal presentation following Session V(b) the Russians reported on the development and application of in-flight simulation in their country. Their simulators have spanned the same range of types and tasks as those in the West starting with VTOL in the 1950's and continuing up to the current SU-27 in-flight simulator of today. They are open for business with the West and would encourage joint research programs.

5. CONCLUSIONS

- The current state of flight simulation and its future course were well documented by the 35 technical papers of this symposium.

- With an attendance of 152 it was clearly a successful meeting and it covered a relevant topic.

- There was a heavy emphasis on military problems and topics. This was present to a greater extent than has been the norm in the past.

- Networking of simulators is obviously increasing and remains an active topic for future developments.

- A number of areas of flight simulation technology are still seen as needing further research and development: visual displays, ground handling models, verification and validation.

- There is an increasing emphasis on cost reduction. The ability of flight simulation to achieve this is one of its strengths.

- Several papers and the keynote address indicated that flight simulation must often fit into an environment of models and software aimed at achieving a number of broad goals.

6. RECOMMENDATIONS

- Researchers in the visual display area should

continue to document the visual needs for the complete range of tasks demanded from flight simulators. The goal should be the ability to select the necessary set of features before undertaking a flight simulator task.

- The time may be right for an AGARD Working Group to assess the state-of-the-art in the field of simulator networking. It appears that significant progress is being made in this area in several countries. A summarizing document could be quite useful for all those involved.

- The current five-year cycle for flight simulation symposia seems to be about right. Another one should be planned for the year 2000.

- The integration of flight simulation into the architecture of broader development environments should be encouraged and be a significant element in the next AGARD Flight Simulation Symposium.

Modeling and Flight Simulation—Tools to Produce Affordable Weapon Systems

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Joint Advanced Strike Technology Program

VISION

"A Joint Services Team creating the building blocks for affordable, successful development of next generation strike weapon systems."

Good morning ladies and gentlemen ! I am very pleased to have this opportunity to kick off this important forum and help focus your thoughts for the next several days on something other than the beautiful country and the great food.

My primary objective will be to challenge you with what I believe are the necessary areas of change and growth that must occur in the modeling and flight simulation disciplines, if we are to remain a major element in achieving system effectiveness.

Let me first describe to you what the Joint Advanced Strike Technology Program is all about and why we have such a strong interest in your success.

We are focused on developing the next generation of strike warfare weapon systems for the US Navy, Marine Corps, Air Force and also, now, the Royal Navy. The program was generated when a number of significant Service modernization programs were canceled due to being unaffordable. The Services and our Department of Defense generated the JAST Program to look for a more affordable way of meeting the Services' strike warfare needs. It was this search for improved affordability that increased our interest in modeling and simulation playing a broader role in weapon system development and operation.

For years, modeling and flight simulation activities have become increasingly important, if not essential, tools in designing, testing, and operating military systems.

These tools were first focused on the tasks of optimizing the lethality or survivability of the weapon system. Later, modeling and simulation became critical to achieving better supportability in our weapon systems.

My challenge to you this morning is to look beyond optimizing system design for lethality, survivability, and supportability and to become a major factor in assuring that our weapon systems are also affordable.

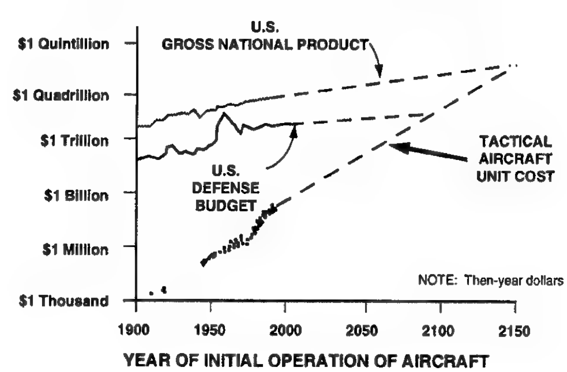
Specifically, your challenge is to structure our modeling and flight simulation tools to achieve a balanced design that produces all four of the necessary characteristics of:

- Lethality
- Survivability
- Supportability
- Affordability

Several years ago, one of the leaders of the US aerospace industry, Norm Augustine, coauthored a book called *The Defense Revolution.*

In this work he described some of the changes that had to occur if the military and the defense industries were to accommodate to the changing world environment. In this book he identified one of the key challenges as stopping what he called runaway techflation.

AUGUSTINE'S LAW - TECHFLATION



Techflation means that, while every new generation of weapon system is far more capable then its predecessor, it also costs considerably more. His prediction is that, by the year 2054, it will take the entire U.S. Defense budget to buy one tactical aircraft.

Clearly, this is an unacceptable trend and must be corrected if our nations are to afford the systems necessary to support our national security policies.

Paper presented at the AGARD FVP Symposium on "Flight Simulation — Where are the Challenges?", held in Braunschweig, Germany, from 22-25 May 1995, and published in CP-577.

We, in the Joint Advanced Strike Technology Program, believe that the modeling and flight simulation community can be the dominant factor in controlling techflation and in helping our Services achieve affordable weapon systems.

For the next few minutes, I will highlight what we believe to be the vision for achieving weapon system affordability through the effective application of modeling and simulation.

MODELING, SIMULATION, & ANALYSIS VISION

Exploit modeling and simulation to create an affordable weapon system by:

- **Supporting early common (government and industry), joint cost-performance trades**
- **Enabling a lower cost design, development, and evaluation process**
- **Providing warfighters early system experience**
- **Enabling more effective system training and employment throughout the program life-cycle**

This chart highlights the primary areas where we believe modeling and simulation can aid in achieving affordable weapon systems.

First you must help the warfighter generate an affordable requirement, that is, a requirement based upon the warfighter understanding their needs—not just their wants—and also an understanding of the cost of the various alternative solutions for satisfying their needs. Our weapon systems must represent a better balance of performance and cost, as do most commercial products. You can help the warfighter with achieving that balance early in the process.

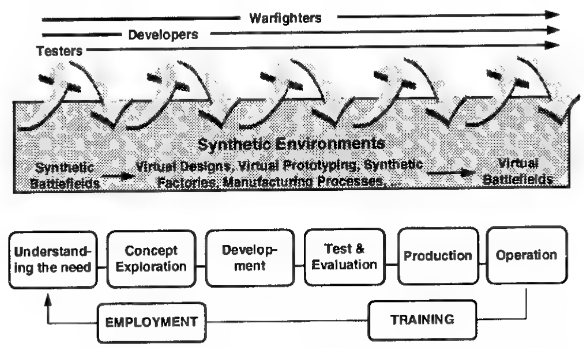
Next, we must expand the role of simulation in the design and development process. We must try to accomplish as much as possible in the virtual world before we build hardware or software or lay out an assembly process.

Next, the developmental and operational test and evaluation process must use flight and ground tests to verify our systems models, and only conduct expensive flight or ground tests as necessary to validate the system models.

Finally, we must design our models, databases, and simulation tools to transition to providing crew-in-the-loop and hardware-in-the-loop applications to support system evaluation, training, and force employment.

From the beginning, these tools must be designed to support distributed activities. Geographically disbursed operations with deployed forces and with coalition partners are becoming the normal mode of operation. Clearly, our modeling and flight simulation tools must adapt to this new environment. This is equally true when most major development programs involve contractor teams that are often international in scope.

M & S SUPPORT FOR THE ENTIRE LIFE CYCLE

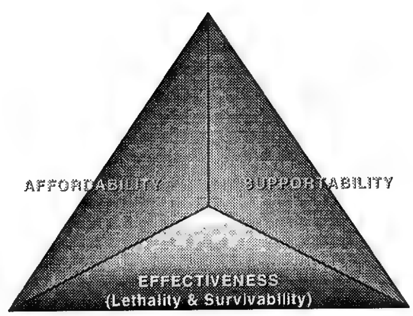


To accomplish these goals, we in the JAST Program have found that you must begin with an objective of fielding modeling and simulation tools to provide life-cycle support for the weapon system.

You must involve the warfighters, the developers, the testers, the cost analysts, and many other communities in the initial design of the modeling and simulation architecture and standards. And once you get buy-in on those standards—you must enforce them!

JAST PROGRAM MS&A MODELING HIERARCHY

FACES OF THE JAST PYRAMID

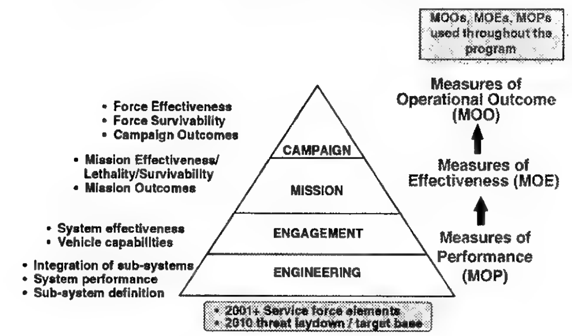


In the JAST Program, we began with a modeling hierarchy that was designed to address effectiveness, supportability, and affordability. For each of these areas we chose core models and benchmarked their characteristics and the associated databases across all government and industry participants. From the beginning, we forced trades between effectiveness and supportability characteristics to achieve affordability. These trades required the modeling environment to develop embedded cost estimating techniques.

The next chart illustrates our approach to the effectiveness modeling. The JAST Program employs six core models to support engagement, mission, and campaign level trades and evaluation.

At the engineering level, besides the normal system and subsystem models, we are creating a virtual avionics prototype that will al-

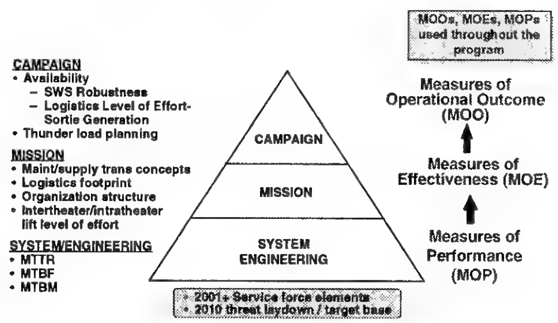
EFFECTIVENESS MODELING HIERARCHY



low us to design and develop the avionics system "virtually" to allow deferral of hardware assembly as long as possible. This allows better exploitation of the latest technology available and provides a more open competitive environment. It will also provide the tools and models to transition into our crew-in-the-loop flight simulation activities.

An important thread of continuity through our modeling environment is created by the constant set of measures of merit. These measures were jointly established by the warfighters and the developers to reflect the necessary characteristics of the system and will be used throughout development and test and then transition into training objectives.

SUPPORTABILITY MODELING HIERARCHY



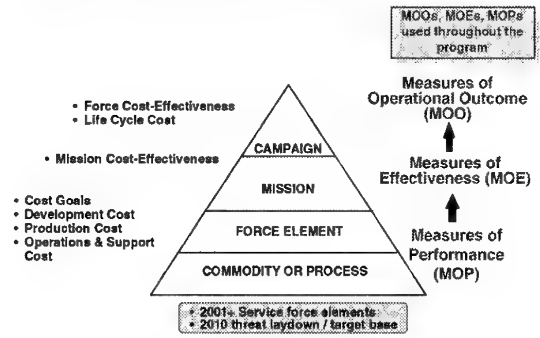
In a similar fashion we identified and benchmarked models for supportability and deployability. In this area we employ three supportability and two deployability models. These models not only address tradeoffs in reliability and maintainability with system characteristics, but also evaluate the impact on supporting airlift and tanker resources.

For each of these models, as was the case for the effectiveness models, we have undertaken the task of joint validation, verification, and accreditation so that senior decision-makers from the Services and the Department of Defense will accept the results.

In the area of affordability modeling, we have taken the process all the way down to the commodity or process level. We found this necessary to ensure that we could effectively employ integrated cost and design databases, and employ cost as an independent variable from the beginning of the system design process.

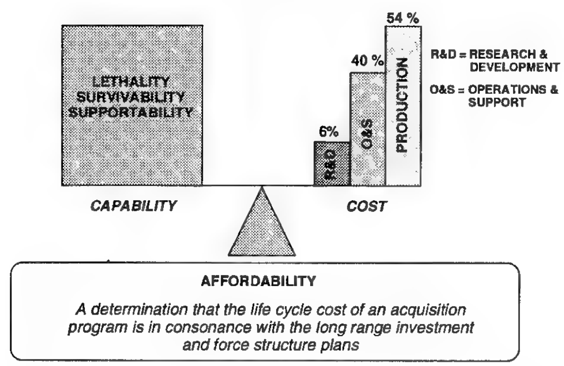
Our objective in employing this constructive and interactive digital simulation is to create a balanced, affordable design that meets

AFFORDABILITY MODELING HIERARCHY



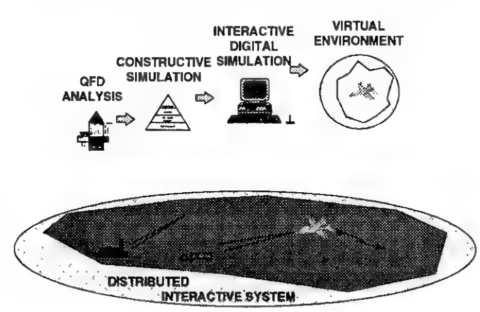
the warfighters' needs. But as this chart depicts, the large payoff is not just in reducing the cost of development, it is in reducing the production and life cycle costs.

AFFORDABILITY OBJECTIVE



As we now take the weapon system concepts into the detailed design and flight demonstration phase, we are finding that the virtual tools we have developed for the tradeoff and design tasks

MODELING & FLIGHT SIMULATION PROCESS



provide the basis for our crew-station design and flight-control developmental activities and eventually will lead to training and mission rehearsal capabilities.

It is this type of life-cycle focus that must be employed as we develop these tools. We cannot afford to build modeling and simulation capability that is limited to unique program phases.

Affordable flight test also results from the effective coupling of modeling and simulation and ground or flight demonstrations. Rather than having the modeling compliment the flight test, we are using the flight or other hardware-in-the-loop testing test to validate the system models.

This approach shows promise for significantly reducing the amount of test resources and test time and, therefore, significantly reducing the cost of these program phases.

From the very beginning, our modeling, simulation and analysis process has been designed to function in a distributed fashion. This was necessary to effectively exploit existing resources and also allowed us to keep all the key agencies involved and participating in the process.

This network will transition to be the backbone for a distributed training and exercise capability. This capability has provided us an early opportunity for the warfighters to evaluate various operational concepts and to develop tactics interactively with the weapon system development.

Unfortunately, our time is limited and you have so many great presentations on the schedule that I must wrap up. Let me summarize with these three key points:

SUMMARY

- **AFFORDABILITY IS AN ESSENTIAL CHARACTERISTIC OF MODERN WEAPON SYSTEMS**
- **MODELING AND FLIGHT SIMULATION CAN PROVIDE FOR EFFECTIVE COST VS PERFORMANCE TRADES AND A MORE EFFECTIVE AND EFFICIENT WEAPON SYSTEM ACQUISITION**
- **SIMULATION ENVIRONMENT MUST BE DESIGNED FOR THE PROGRAM LIFE-CYCLE AND SUPPORT DISTRIBUTED, MULTI-LEVEL OPERATIONS**

First, affordability is an absolutely essential characteristic of our new weapon systems. Affordability will only occur when we pay as much attention to it as we do the other essential performance characteristics of our weapon systems.

Modeling and flight simulation can be an important tool in achieving a balanced, affordable design and in supporting that design throughout its lifetime. However, this will only occur if we evolve our modeling and simulation tools to treat cost and affordability as a major program objective.

As you can see from this brief description, the JAST Program is dependent on this community to deliver the tools to achieve lethal, survivable, supportable, and ***affordable*** weapon systems. We actively solicit your help in working this most difficult challenge.

At this time, I would be happy to answer a few questions. As I do that, this chart identifies the most effective way of getting additional information on the JAST Program or for providing us your ideas.

Thank you for your attention.

JOINT ADVANCED STRIKE TECHNOLOGY PROGRAM
U.S. NAVY U.S. MARINE CORPS U.S. AIR FORCE

For further information, contact the JAST Program Office on the World-Wide Web (Internet)

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Historical Review of Piloted Simulation at NASA Ames

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ABSTRACT
This paper traces the conception and development of in-flight and ground based simulators at NASA Ames Research Center, starting in 1947 and continuing to the early 1990's. Problems with their development and operation and how limitations were handled are recounted. Advances needed in simulator equipment to improve performance and fidelity to gain pilot acceptance are discussed. The uses of these simulators in various aircraft research and development programs and their importance to aircraft design and flight testing are reviewed. Challenges remaining include a better understanding of the tradeoff between motion cues and visual cues, the importance of simulation sophistication when examining aircraft with marginal handling qualities characteristics, and the continuing need for upgrading simulation technology as more complex problems are encountered. Additional research is needed to understand the human behavior aspect in the pilot/simulator system.

INTRODUCTION

Both ground based and in-flight research simulators have proven to be valuable assets to aid design and development of a wide variety of aircraft. At the NASA Ames Research Center, the development and use of piloted flight simulators which started in the late 1940s has continued with an improved range of capabilities. Early on, the need for improved realism both in terms of cockpit motion cues and visual displays was recognized as more definitive answers were required for more complex problems. As a result, simulators were designed and developed to provide two, three, five, and finally six degrees of motion freedom, and visual displays increased in sophistication to provide out-the-window, wide field of view scenes approaching real life quality. In-flight simulation which started in 1947 with a WWII F6F aircraft has utilized a variety of aircraft including fixed wing, V/STOL, and rotorcraft configurations. They functioned as new flight research tools to study old and new problems with varying degrees of success.

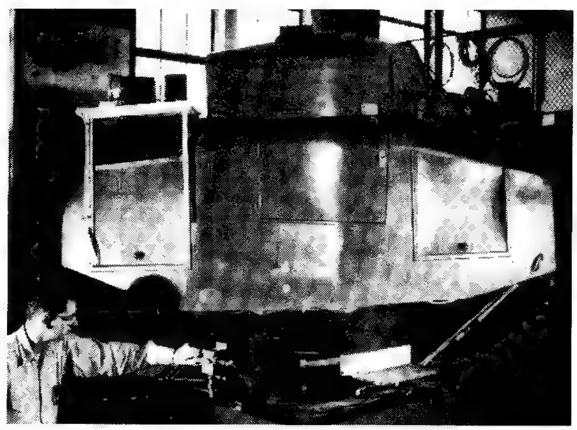
One may ask about the future for research simulators at the turn of the century. A partial answer may be found by examining the past to learn what was needed to continue advancement in simulator technology. It is convenient to review the history of piloted simulator development at NASA Ames where simulation has developed into a major national research facility. About a dozen ground based and an equal number of in-flight simulators have been developed at Ames, each having a limited life span. The purpose of this paper is to review the history of piloted flight simulation to focus attention on the challenges remaining for continued improvement.

The scope includes a brief description of several select ground based and in-flight simulators used in research studies at NASA Ames Research Center, examples of results obtained, and a review of the problems (and solutions) encountered along the way.

DISCUSSION

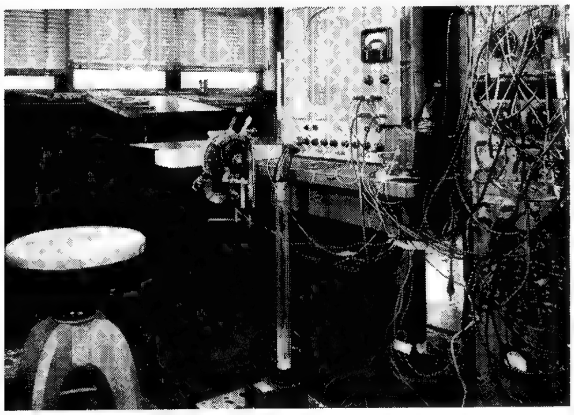
Description and Research Projects

Link "Blue Box" procedures trainer The first piloted simulator (fig.1) at Ames was one that introduced the era of flight simulation (1929) and served as an IFR procedures trainer during WWII. It had 3 degrees of angular motion and only a basic IFR (needle, ball and airspeed) visual system. Attempts to improve the drive system which used pneumatic valves, bellows, and actuators originally created to make organ music, proved futile and no research results were obtained. It was relegated to become a museum artifact, but remains operational to show how far simulation has come.



Rudimentary fixed base The first application of piloted simulators for aeronautical research originated in the NACA time period (1955), as part of a study to develop criteria for selecting carrier landing approach speeds (ref. 1). This simulator (fig.2) was very rudimentary, consisting of a control stick geared linearly to aircraft lift coefficient (no stick force gradient) through a first-order time constant, a throttle geared linearly to thrust, a stall-warning audible buzzer, a visual presentation of an airspeed indicator and a CRT showing altitude (horizontal line) above a ground reference with a shorter horizontal line to indicate vertical acceleration. These visual references were selected to give information on control of altitude, the primary reason given by pilots for selecting the minimum airspeed in most carrier approach landings. An analog computer was used to model basic flight characteristics for each of three carrier type aircraft.

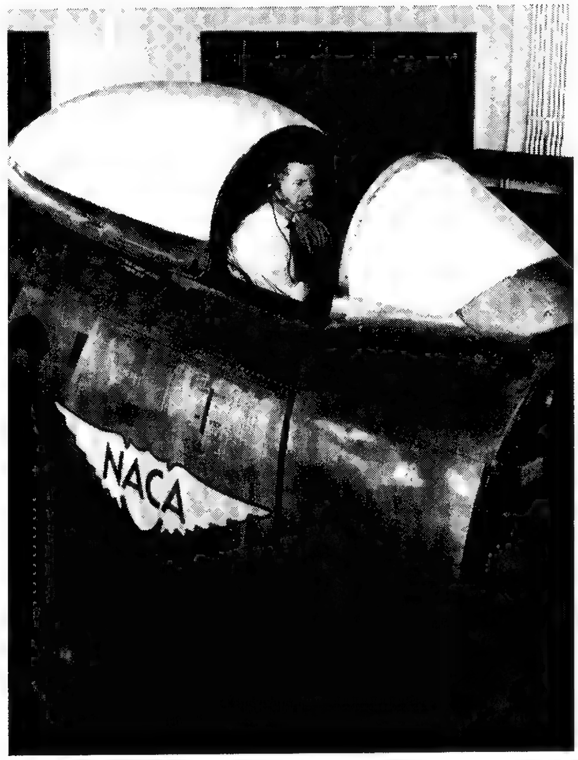
Paper presented at the AGARD FVP Symposium on "Flight Simulation — Where are the Challenges?", held in Braunschweig, Germany, from 22-25 May 1995, and published in CP-577.



Initially, the pilots were skeptical that the crude simulator environment would provide any degree of correlation with flight. However, after suitable adjustments were made to such items as stick gain (C_L per δ_e), throttle response, and thrust margin, reasonable correlation with flight was achieved for approach speeds (within 3 knots) for several Navy carrier aircraft. However, because of the use of a "generalized" math model, lack of cockpit realism and lack of associated motion response, the pilot could not "identify" flying a particular aircraft, thereby restricting correlation to only those conditions where altitude control was the primary factor for selecting minimum approach speed. The challenge that remained was to provide the sophistication needed to determine minimum approach speed when other factors such as adverse stability and control characteristics were dominant reasons for choosing approach speed.

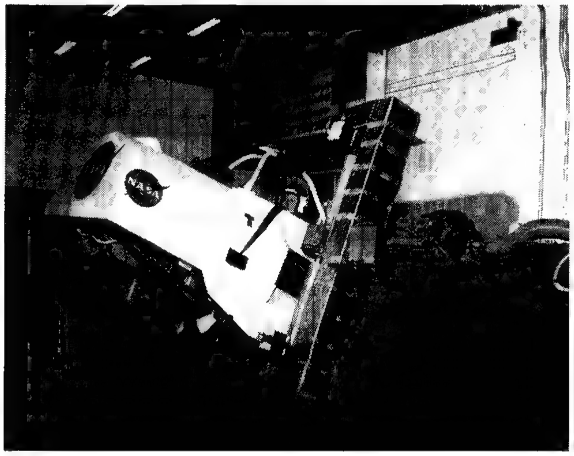
In part because of the lack of motion cues, a form of atmospheric disturbance was needed to provide flight path excursions similar to those encountered in actual approaches since this factor directly impacts ability to control altitude and therefore selection of approach speed. Although the pilots were less than enthusiastic about the credibility of their answers, this early study showed the potential for using piloted simulators to study important aircraft operational problems.

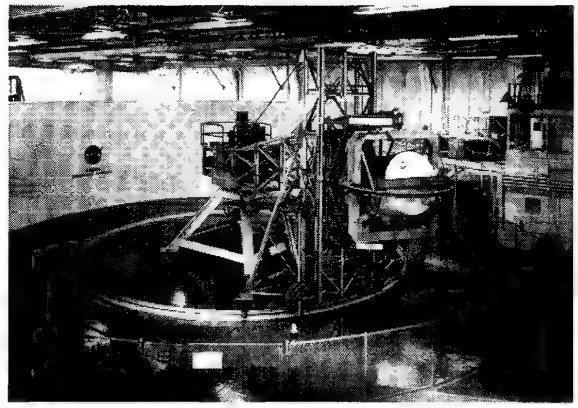
F-86A/D cockpit simulator Recognizing the need to improve cockpit realism, a fixed base simulator (fig.3)was made operational in 1958 using of the forward half of an F-86A/D airplane with the cockpit interior and controls closely resembling those of the actual airplane. The cockpit could be covered with an opaque canopy to isolate the test pilot from outside distractions or left open to provide a real-world view. The only cockpit instrument was a 5" oscilloscope, which was used to display attitude and a target for a tracking task in a study of the effects of longitudinal control-system dynamics (ref. 2), and bank angle for a study of lateral control requirements for fighter-type aircraft (ref. 3). The drive signals to the oscilloscope were provided by an analog computer which solved the equations of motion for the airplane.



These early studies showed that good correlation with flight test results was restricted to areas where handling qualities were satisfactory. Correlation with flight results was poor when exploring areas of low damping and poor stability or when investigating control characteristics conducive to pilot induced oscillations (PIO). Although the F-86 cockpit added realism, the lack of motion cues and an adequate visual scene tended to produce results which were too conservative.

NE-2 simulator The need to improve accuracy in establishing control system requirements by using motion cues resulted in the first *motion* research simulator (fig.4) introduced in 1959. It was called the NE-2 ("any two") because its gimbal arrangement provided mounting for roll and pitch, pitch and yaw, or yaw and roll motion. Approximately $\pm$ 45 deg angular motion was provided by an electric motor. An analog computer provided outputs for angular position, rate, and acceleration. The cockpit controls were similar to those of an actual airplane. Control requirements for a VTOL hover task were studied (ref. 4) with an open cockpit view of the outside world. In studies of lateral control requirements for fighter-type aircraft, the cockpit was covered, and a CRT and a limited number of panel instruments provided aircraft state information.





Although use of this first motion simulator was short lived, several tests of historical interest indicated the importance of providing motion feedback. For example, an engine failure for the YF-12 aircraft in cruise (Mach 3) showed the need for motion cues to develop an operationally acceptable control system to avoid catastrophic directional divergence. In another case, a test pilot from the U.K. was given an opportunity to sample the hover control characteristics of the X-14 VTOL aircraft, before starting flight tests of the British Harrier VTOL aircraft. The motion and visual cues provided in the practice runs in the simulator were inadequate since when flying the real aircraft lateral drift was not eliminated before touchdown, severely damaging the X-14.

The motion cues did provide more accurate pilot opinion ratings of control power and damping requirements for hover operation of VTOL aircraft using an open cockpit visual scene. The pilots were able to use the roll angular acceleration cues to define satisfactory levels of lateral control power; however, large amplitude roll angles were disorienting because of unrealistic side forces imposed on the pilot. Two axes motion feedback provided better correlation with flight particularly for simulation of VTOL hovering when poor stability and low damping aircraft characteristics prevailed. For studying fighter aircraft maneuvering control requirements, the motion characteristics were inadequate restricting studies to simple one axis tracking tasks where control cross coupling was essentially non-existent. Multi-axis motion feedback including vertical and side force cues remained as an important challenge for the future.

Five degree of freedom simulator This simulator (5DOFS) (fig. 5) introduced in 1960 was designed for use as a piloted centrifuge test facility. It had a three-gimbaled cab mounted on a vertical track which, in turn, was mounted on the end of an 30 ft. arm (ref. 5). A circular rail on the floor supported the vertical track assembly. Two interchangeable single place cabs were available: one, representing a conventional aircraft had the pilot facing radially outward, whereas the other, representing the pilot seated in a spacecraft, was mounted facing radially inward. In the former case, changes in side acceleration at the cockpit could be simulated by angular acceleration of the centrifuge arm. Electromechanical servo systems driven by d.c. electrical motors provided rotary degrees of freedom, $\pm 90°$ in roll, $\pm 40°$ in pitch, $\pm 70°$ in yaw. Translational motion was available in two directions, ± 1.75 ft. vertically and unlimited sideward movement by rotating the centrifuge arm. A single-place cockpit was equipped with a stick control, two throttles, and conventional flight instruments. In the three angular degrees of freedom mode, an external view of the real world was used. The cockpit was covered with an opaque canopy for conditions where side acceleration cues were required (ref. 5). In 1969, a televised visual display was installed in the cab. General purpose analog computers were used to generate the commands for the motion system and instruments (ref. 6).

The 5DOFS was used to study handling qualities requirements for supersonic transports (refs. 5, 7, and 8). Two historical contributions are of interest. One was its use in the Gemini spacecraft program to subject astronauts to vibrations with the same frequencies and amplitudes as those that had been measured on the Titan launch system. These frequencies were in the critical range (3 to 10 Hz), which might debilitate astronauts during liftoff. The other historical contribution was a non-aerospace use of the simulator (1968) where a bullet fragment in a patient's brain was repositioned by centrifugal forces to a "safe" location.

The 5DOFS centrifuge design did not provide a significant advance in the state-of-the-art for aircraft research studies primarily because of motion deficiencies. (The 5DOFS was dismantled in 1975.) Providing only a small amount of vertical travel was ineffective since strong (disorienting) washouts were required to avoid hitting stops. In addition, since the cab was not counter balanced, dynamic response was non-linear; downward acceleration was fast and vice versa; therefore this motion was not used in research studies (ref. 7). Attempts to accurately reproduce and sustain side accelerations resulted in large velocities of the centrifuge arm which were objectionable to the pilot because of vibration (noise) and centrifugal acceleration effects. The use of washout to minimize the adverse centrifugal effects met with only limited success. In addition, dynamic response was poor due to cable stretch. Use of this facility for centrifuge research studies was not undertaken because of large amplitude vibration levels associated with the rail support system and safety concerns when tangential velocities of 60 mph were reached at 5 "g" acceleration. A

challenge remained to provide non-disorienting translational motion cues in a yet to be defined geometric area.

Basic simulator with external horizon Another fixed base simulator, housed in a 20 ft diameter dome was used briefly in 1961 to investigate the value of extensive peripheral vision cues. The cockpit was similar to that of a F-86E airplane, with conventional rudder pedals, center stick, and flight instruments. The simulator had a novel visual system employing a two-axis servo-driven (roll and pitch) motion picture projector, controlled by an analog computer, to project a moving artificial horizon onto a 20-foot-diameter hemispherical screen. To the pilot, the image appeared to be a brightly illuminated layer of clouds several thousand feet below the cockpit. Another projection method used an approach and touchdown scene obtained from a 16mm camera located in the cockpit of a fighter aircraft.

The simulator was used in a study of the effect of lateral-directional control coupling for supersonic and hypersonic aircraft (ref. 9). Although the wide field of view provided a good bank angle reference, limitations of the visual scene content and lack of motion cues discouraged extensive use of this simulator. The strong visual cues supplied by the wide field of view horizon projector in the absence of motion cues were disorienting when large amplitude roll excursions were used. When the visual system was used for approach and landings with the preprogrammed movie scene, the results were only of subjective interest since no matter how poorly the pilot flew the aircraft on approach, a perfect landing always resulted. Projecting a usable real world scene over the large area of the dome required considerably more light intensity than was available at that time.

Transport landing-approach sim-ulator In part because of the lack of success with the motion system of the 5DOFS, and the immediate need for research results in landing approach for transports, another fixed based simulator was developed (1961). This simulator (fig.6) had a fixed-base transport-type cockpit, a

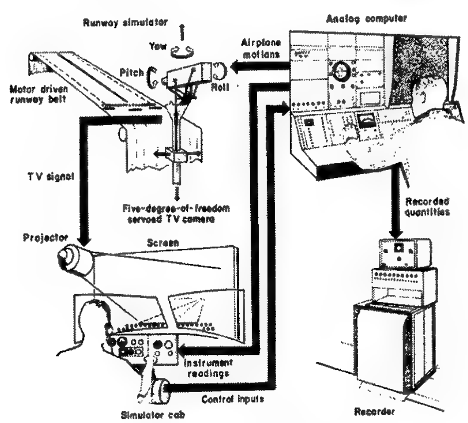


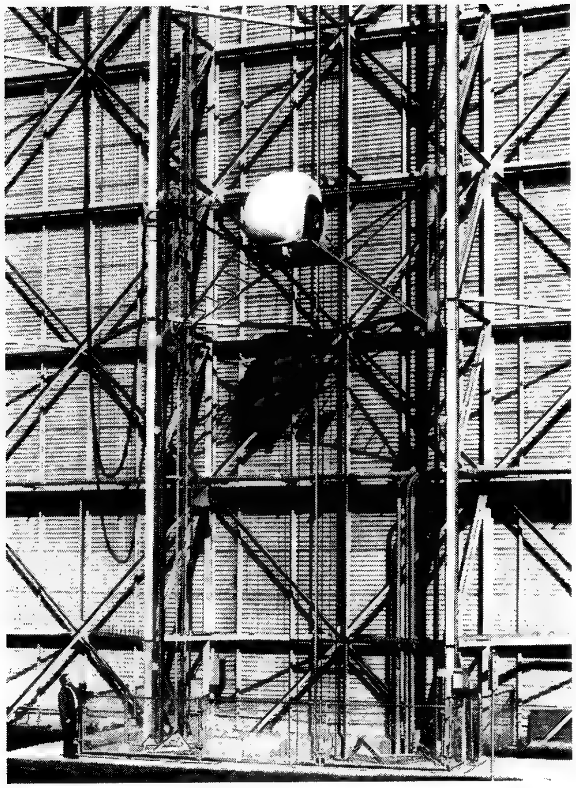
Figure 6. Transport Landing-Approach Simulator

conventional cockpit instrument display, normal flight controls (with control forces provided by springs and dampers), and a general purpose analog computer programmed with math model equations of six degrees of motion freedom.

An important addition was an out-the-window view of a runway generated by a Dalto Visual System developed for use with training simulators. It consisted of a television camera servo-driven in three angular degrees of freedom, and vertical and lateral displacement relative to a runway model installed on a continuously moving belt. The resulting television scene, projected onto a screen mounted about 10 feet forward of the simulator cockpit, showed the approach lighting and runway as seen in a landing at dusk with hazy, one-half-mile visibility.

This simulator was used for several handling qualities studies including a supersonic transport configuration in landing approach (refs. 7, 10, and11) and for lateral-directional evaluations of a large STOL transport airplane (refs. 12 and 13) Although the addition of the Dalto visual system to a fixed base simulator had a beneficial effect on pilot evaluations of handling qualities, all pilots had difficulty making consistent landings, due in part to the lack of motion cues which normally provide useful lead information. To help the pilot "calibrate" the simulator for the landing task, an opportunity to "fly" a known aircraft proved to be beneficial. Better correlation with flight was obtained after the simulator cockpit mechanical control characteristics were modified to provide control centering and low friction so the pilot could obtain a "feel" of the aircraft in the absence of motion feedback. The deficiencies of this visual system (ref. 14) adversely affected precision of landing performance due in part to poor resolution inherent in black and white television projection and other undesirable features including mechanical backlash, noisy drive signals, unsteady video performance, and lags in the camera drives. Lateral/directional handing qualities evaluations were compromised particularly for STOL aircraft which were maneuvered more extensively by the restricted peripheral visual cues inherent in the TV system.

Height control test apparatus (HiConTA) In the same time period (1961), a somewhat unique (single degree-of-freedom) simulator (fig. 7) was built for the primary task of studying height control requirements for VTOL aircraft. Attached to the structural framework of the 40x80-ft Wind Tunnel, it provided a relatively large vertical travel (100 ft) and a true outside world visual scene. A two-place helicopter cab was suitably equipped for several studies; helicopter cockpit controls for VTOL aircraft, transport type controls for a jet transport control problem study, and a conventional stick for a low level, high speed terrain following program (ref.15). In each case, cockpit panel instruments provided the pilot with essential (but meager) information for each of the test situations. In addition, for a landing performance study (ref. 16), a TV system displayed a night runway scene on a black and white 16 in. TV monitor.

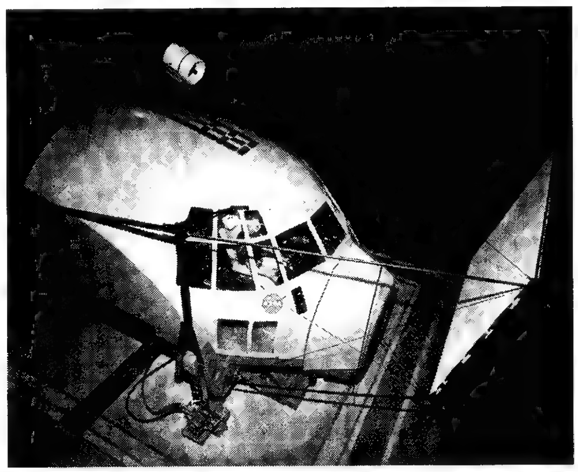


The vertical motion system was driven in response to the analog computed cockpit vertical acceleration modified by high-pass filtering (wash out) to constrain the cab to acceptable excursion limits. A lead network was required to reduce lag in the electric motor drive system. Accelerations of $\pm$ 2g and maximum velocities of $\pm$ 20 ft/sec were possible. The frequency response was essentially flat out to 1 HZ.

The single degree of freedom (heave) motion was sufficient for the specialized VTOL height control task, and good correlation with flight was achieved (ref. 17). Landing performance measurements (touchdown velocities) correlated well with flight (ref. 16); however, considerable pilot adaptation (landing practices) was required to achieve consistent results in part due to lack of other motion cues and limited visual cues from the TV display. This was helped by flying a "known" aircraft. The vertical dynamics (frequency and amplitude) inherent in the cable/drive system realistically simulated structural cockpit motion for transport jet aircraft when used in studies to determine reasons for loss of flight path control when flying in large scale atmospheric turbulence. (ref. 18).

For landing performance studies, only 40 ft ($\pm$ 20 ft) of vertical travel was needed to obtain desired fidelity using acceptable "wash out" frequencies, and $\pm$ 20 ft/sec vertical velocity capability. Motion system noises (track rumble) detracted from simulation fidelity giving false velocity cues. The amount of available vertical travel was larger than necessary, with adverse implications on safety, dynamic response (cable stretch), and maintenance. Improved sophistication in terms of visual displays or additional degrees of freedom were not possible with the cab because of the adverse effect of added weight on dynamic response. The HiConTA was dismantled about 1984.

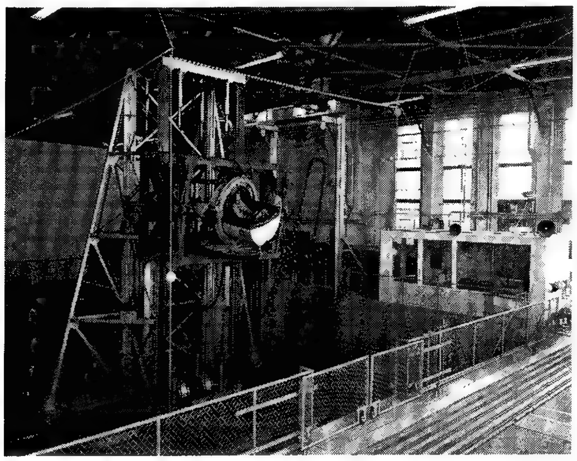
Moving base transport simulator Motivated by the need for improved accuracy in developing handling qualities criteria for STOL aircraft, another simulator (fig. 8) became operational in 1963. The motion system used three linear hydraulic servo actuators, which operated differentially or in synchronization to provide roll angles in the range of $\pm 9°$, pitch angles from -6° to +14°, and a small amount of vertical travel (2 ft.). A transport cab was used with conventional seating for two pilots, instrumentation, and controls which were hydraulically powered for variation of control system parameters. Initially a scene of the approach lighting and runway was projected onto a screen outside the cab by the Dalto visual system. Later, the Redifon color TV system was implemented. The drive signals for the motion system, instruments, and visual system were generated by an analog computer.



This facility was used for a variety of studies, including several carrier landing aircraft, handling qualities requirements of a STOL seaplane (ref. 19), STOL aircraft (ref.20) and 21), and a special purpose counterinsurgency (COIN) aircraft. The very limited amount of vertical motion (2 ft.), was not usable in STOL landing approach studies because of adverse dynamics response characteristics associated with large wash out requirements. When the roll motion was programmed to provide a 1-to-1 ratio of input bank angle to cab motion, large bank angles typical of STOL operations could not be used because the pilot objected to an unrealistic side force. Also, without yaw capability, roll /yaw crosscoupling problems could not be studied. The addition of the Redifon color system was a strong factor in improving pilot acceptance of handling qualities results and compensated to some degree for the lack of yaw and heave motion. This simulator had a long history of successful use and was finally dismantled circa 1984.

All-axes motion generator Based primarily on the need to provide more definitive control system design values for VTOL aircraft, the first six-degree-of-freedom motion simulator at Ames (fig. 9) was put into operation in 1964. The single place cab could move $\pm$ 45° about the pitch, roll, and yaw axes and

translate ± 9 feet in three orthogonal directions. This simulator was one of the first to use equilibrators, instead of a counter-weight to help offset gravitational effects and thereby improve vertical dynamic performance. A conventional center stick, rudder pedals, and a fighter-type throttle quadrant were provided An analog computer system generated the drive signals for the motion system and instruments.



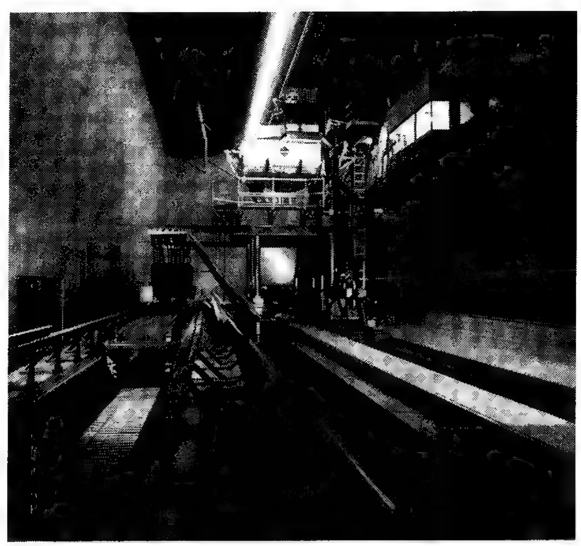
Operational safety was a primary concern. A shock absorber system was developed to avoid excessive loads at the extremities of travel. Several large orange colored balls were appropriately located in space to warn the pilot of impending travel limits. In addition, the electric drive system would automatically shut off if the pilot commanded too large translational velocities when approaching limits of travel. On a few occasions, the cockpit restraint system (pilot safety belts) proved valuable when the cab was inadvertently driven hard-over to the extremities of all six degrees of freedom.

The simulator validated its intended design features by providing the real-life sensations of VTOL hover operation (ref. 22). Hangar doors could be opened for a natural outdoor scene, and VTOL hover tasks could be conducted without motion washout and the results showed good correlation with flight. The opportunity to evaluate advanced control systems was valuable in preparing for a cooperative flight test program of the German DO-31 VTOL jet transport aircraft. Translational control requirements for lateral positioning in hover, (ref. 23) defined the magnitude of side acceleration needed to translate without banking, which correlated well with flight tests in the X-14B VTOL aircraft. Of historical interest, this simulator was used by the Apollo Lunar Landing pilots, starting with Neil Armstrong, to simulate lunar landing dynamics (ref. 9).

Only a limited amount of testing was conducted with a hooded cab using a 16" CRT Redifon TV system. Later, the simulator was modified to permit repositioning the cab to a nominal 90° pitch-up angle (pilot was lying on the back) for vertical attitude take off and landing (VATOL) concepts.

The travel within an 18 ft cube VTOL limited control evaluations to a hover maneuver task. More extensive translation motion than available was desired for evaluating more sophisticated systems such as velocity command control. Although the outside view provided flight-like realism, the pilots still felt the confining effect of the inner walls of the building. Providing six degrees of motion freedom did not in itself guarantee high utilization of this simulator. The single place cab and low quality cockpit visual display available at that time, discouraged more extensive use. In addition, for large lateral maneuvers the required wash out accelerations were larger than the pilot's input values, and were disorienting. Safety requirements to limit translational velocities caused frequent shut down of the drive system and inconvenient reset procedures for start up. The suspended heavy utility cable introduced undesirable (spurious) cab motion. The use of equilibrators successfully improved vertical dynamic response and were used on subsequent motion simulators.

Flight simulator for advanced aircraft (FSAA) Past experience in simulation of large aircraft had pointed out a strong need for multi crew cabs with more extensive translational motion capabilities. Accordingly, the FSAA (fig. 10) became operational in 1969 (refs. 24, 25, and 26). This six degree of freedom motion system, using DC velocity servo drives, provided an extended lateral travel (± 40 ft), vertical travel (± 4 ft) and fore and aft (± 3-1/2 ft) motion. Two tractors moved the simulator laterally, with supporting wheels taking the principal vertical loads. The lateral carriage carried a vertical platform raised and lowered by three continuous ball screws. To unburden the screw drive, equilibrators were used to float the vertical platform. On top of the vertical platform was the longitudinal motion system which used a single ball screw to drive the cockpit and gimbal systems fore and aft. Relatively conventional chain-drive gimbals provided three angular motions. For operational safety, the position, velocity, and acceleration of each motion system axis were constrained by an array of electrical limiters and ultimately by mechanical buffers. The analog computer initially used (ref. 27) had so many elements that the program could not be quickly and thoroughly checked.



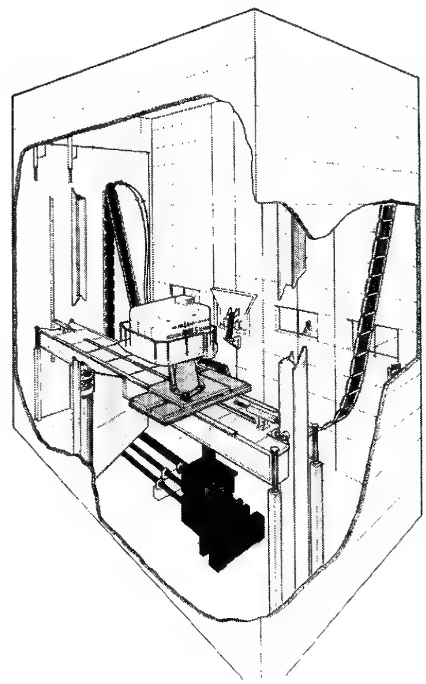
A compensation circuit (ref. 25) was required to reduce the "turn-around-bump", a disturbance which could occur every time a motion drive reversed direction in the lateral and vertical drives.

The FSAA was a major step up in simulator sophistication offering for the first time a 3 place cab with full motion including a uniquely large lateral travel range which provided more realistic side force cues associated with engine failure for transports where the pilot's position is far forward of the C.G. and for turn entry maneuvers peculiar to STOL aircraft. A wide range of notable aircraft research and development programs used the FSAA including Supersonic Transport (Concord), many V/STOL aircraft, and the Space Shuttle Orbiter. (ref. 28).

Although the FSAA proved quite useful in several important research programs, it had basic limitations which would eventually limit its service life. The need to provide good motion (travel) harmony was not fully appreciated in the design of the FSAA. Less lateral travel would have been acceptable, but considerably more vertical travel was needed. The extensive lateral travel was a constant source of maintenance. Investigations found that the FSAA had limitations in matching flight performance in control of flight path near touchdown (ref. 29), indicating that available vertical motion cues were inadequate to provide high-fidelity simulation of flare and touchdown. The fore and aft travel (± 3.5 ft.) was adequate for conventional aircraft simulation; however more travel was needed for simulation of low speed maneuvers with VTOL aircraft and rotorcraft. The realism of the simulation was compromised by a velocity-related audible noise in the lateral drive motion system (refs.25 and 26) and required amplification of aural cues of the engine to mask this disturbance. The Redifon TV visual system, although providing real life color cues and a well appreciated go-around capability was limited in diversity for multi task operation and by the narrow field of view. The FSAA was dismantled circa 1985.

Vertical motion simulator Building on the lessons learned from the FSAA operation, an improved simulator (VMS) (fig.11), began operation in 1980 with a better match in motion harmony. Compared to the FSAA, it had extended vertical travel and less than half the amount of lateral motion. In 1987, a major upgrade to the VMS (refs. 30 and 31) provided enhanced motion capabilities and visual cues. The VMS (ref. 33) utilizes a large aluminum platform supported from below by two pneumatic equilibrators, each of which is driven vertically (± 22 ft) by four dc servo motors. The lateral travel (± 15 ft) is provided by a carriage moved across the platform by four d.c. servo motors. A hydraulically driven four degrees-of-freedom motion system provides angular-rate and acceleration capabilities and longitudinal displacement (± 3 ft). A programmable vibration generator system, was needed for high frequency, low amplitude accelerations, characteristic of helicopter vibrations.

Four interchangeable cabs (ICABs) are available to simulate a variety of aerospace vehicles. A three-window two-seat side-by-side configuration is used for simulating transport aircraft or the Space Shuttle, two four-window configurations are used primarily for simulating helicopters and V/STOL aircraft, and a three-window continuous wraparound configuration for single seat fighter aircraft. Cockpit controls for various aircraft configurations with realistic force-feel cues are provided by a programmable McFadden control loader system. A collimating mirror/beam-splitter system is used with an Evans and Sutherland (E&S) CT5A CIG system. Four speakers mounted in the cab are needed to reproduce a variety of sounds associated with different types of aircraft and helicopters.



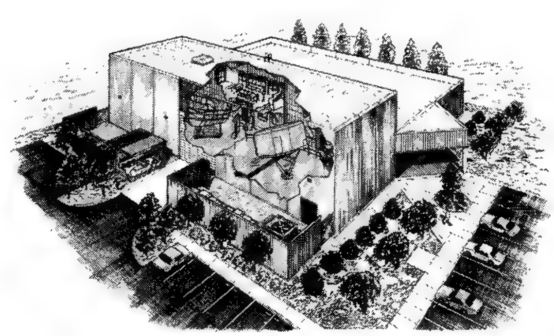
The first use of the VMS was a Space Shuttle approach and landing study .. The VMS has continued to be used by Astronauts to examine important operational characteristics. The XV-15 tilt rotor aircraft design, flight experiments, and handling qualities (ref. 32) were carried out using the VMS. Other major research and development programs include the UH-60 Black Hawk Helicopter, LHX Helicopter, RASCAL, YAV8B Harrier, STOVL Fighter Attack Aircraft, Oblique Wing, Automated Nap-Of-The-Earth Rotorcraft Guidance, Helicopter Terrain-Following Terrain-Avoidance System, VTOL Flight Controls and Display Concepts for Shipboard Operations, Computer Aided Guidance for Low-Altitude Helicopter Flight.

The ICAB feature provided increased utility and efficiency in conducting research on a wide variety of vehicle concepts. The ability to reconfigure, check out, and use a cab for fixed-base simulation in a separate development area has proved invaluable. The advent of digital computers and in-house development of remote input/output interfaces have reduced greatly the number of electrical and data leads connected to the cab thus improving reliability and reducing maintenance. There is a continuing need for increasing computational capacity to model more advanced vehicle/rotor configurations, advanced rotorcraft on-board systems, and integrated flight/propulsion

control. The replacement of the TV terrain model visual system with CIGs was needed for a much improved field of view, clarity, and scene content and detail. Lead compensation (ref.33) was required to remove inherent transport lags.

The VMS with existing motion capabilities and improved visual system has received a high degree of pilot acceptance for the majority of test programs. However it still lacks the ability to accurately simulate all the conditions conducive to PIO or the complex aero/structural/control interface for the VLA transport. In addition, pilot criticism of motion roughness and noise, occasional occurrences of "simulator sickness," and reference to lack of depth perception remain as other important challenges for improvement.

The crew-vehicle systems research facility (CVSRF), A major change in simulator equipment occurred in the mid 1980's. (ref.32). Previous simulators were designed to study aircraft stability and control problems and define boundaries for satisfactory control. As aircraft control systems grew in complexity so did the human/machine interface and the need for specialized simulation research tools. This equipment (figure 12) was designed primarily to study human factors in aviation safety. (ref. 33) The CVSRF allows scientists to study how errors are mad, as well as the effects of automation, advanced instrumentation, and other factors, such as fatigue, on human performance in aircraft. The facility is used to analyze performance characteristics of flight crews; formulate principles and design criteria for future aviation environments; evaluate new and contemporary air traffic control procedures; and develop new training and simulation techniques required by the continued technical evolution of flight systems. The facility includes a Boeing 747-400 flight simulator, the Advanced Concepts Flight Simulator (ACFS), and a simulated Air Traffic Control (ATC) system simulator. Both flight simulators are capable of performing full-mission simulations.



The Boeing 747-400 simulator represents a current technology state-of-the-art glass cockpit aircraft in an environment that ensures that aircrew behavior in simulated flights is representative of actual flight operations. In contrast, the ACFS, configured with multiple electronic displays, advanced crew-aircraft interfaces and flight control devices, is designed to permit virtually unlimited flexibility in information presentation, and command and control by the aircrew. Such flexibility permits the simulation of operations that may be possible with advanced aircraft and air traffic control concepts and equipment of the future. The ATC system simulator provides a realistic ATC environment, including communications systems as they impact crew performance.

The Boeing 747-400 flight simulator is equipped with programmable flight displays that can be easily modified to create displays aimed at enhancing flight crew situational awareness. The simulator also has a fully digital control loading system, a six degree-of-freedom motion system, a digital sound and aural cues system and a fully integrated autoflight system which provides aircraft guidance and control. It is also equipped with a weather radar system simulation and a Flight Safety International VITAL VIIe visual system. The visual system can depict out the window scenes in either day, dusk, night, or twilight modes. The visual, weather radar, and motion systems are tightly coupled, simulating weather effects with a high degree of realism. The Boeing 747-400 simulator provides all modes of airplane operation from cockpit preflight to parking and shutdown at destination. The simulator flight crew compartment is a fully detailed replica of a current airline cockpit.

Like the Boeing 747-400 simulator, the ACFS is also equipped with a six degree-of-freedom motion system and is equipped with a Link-Miles Image II visual system. This unique research tool is a generic commercial transport aircraft simulator employing many advanced flight systems as well as features existing in the newest aircraft being built today. Among its advanced flight systems, the ACFS includes touch sensitive electronic checklists, advanced graphical flight displays, aircraft systems schematics, a flight management system, and a spatialized aural warning and communications system. In addition, the ACFS utilizes sidestick controllers for pitch and roll control axes. The ACFS generic aircraft was formulated and sized on the basis of projected user needs beyond the year 2000.

Some typical research programs that have been conducted at the CVSRF include Complex Air Traffic Control Procedures to evaluated the advantages and benefits of advanced curved approach and departure procedures (using the Microwave Landing System) for high density aircraft operations; the Data Link Project which demonstrated the feasibility of displaying real-time weather data; Advanced Glass Cockpit Design study, which evaluated the usefulness of electronic checklists for coping with onboard malfunctions in highly automated aircraft; Triple Parallel Runways Experiments, in cooperation with the FAA which evaluated the capability of multiple (triple and quadruple) parallel runways to increase airport capacity in a safe and acceptable manner. Other simulations supported by the CVSRF in the near term include support of the NASA High Speed Research (HSR) and Advanced Subsonic Technology (AST) focused programs, as well as support of FAA programs including the study of Terminal Area Productivity and Air Traffic Management .

A remaining challenge in the use of this facility is how to evaluate simulation results in terms of human behavior and limitations in the total human/machine interface.

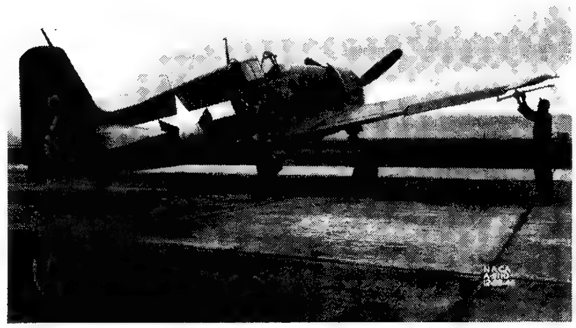
The Future Of Ground Based Research Simulators

Based on past experience, future development of piloted research simulators at Ames will hinge for the most part on improvements in its subsystems. It is not expected that any major changes in motion travel will be made, however reducing time delays of the motion system response will be needed for solving more complex problems with visual/motion/model mismatches. Improvements in the cab environment will continue with better acoustic engineering and better lighting realism. Also expected is the greater use of the "glass cockpit", with all-digital displays and voice interactive systems in simulation of advanced aircraft. A needed advance in technology will come from the use of later generation CIGs to improve realism of flight. In addition, advances in computer technology will allow an increase in sophistication and complexity of simulation models. Other future developments will reflect the need to simulate advances made in the cockpits of future transport aircraft to allow the pilot's view to be augmented by a combination of sensor data, previously stored data, and real-time data received through aircraft data links to create "virtual reality", meaning that the pilot's view need not be tied to the pilot's eye location.

In-Flight Simulation

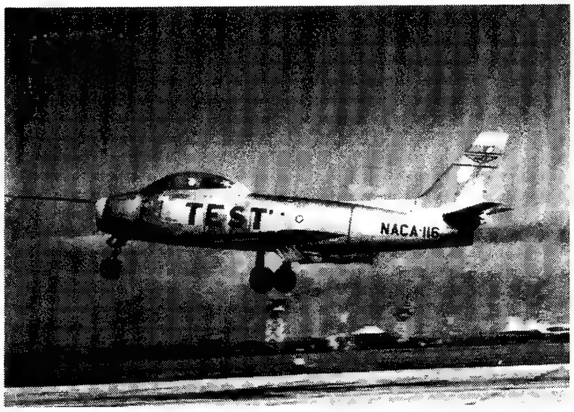
The use of actual aircraft as in-flight simulators started at NACA Ames in 1947, several years before ground base simulators were developed. The use for in-flight simulation was driven by the need to examine and define specific handling qualities related primarily to dynamic (oscillatory) aircraft behavior. Because the principal use was to study a range of stability derivatives with varying degrees of control authority, the name "Variable Stability and Control" (VSC) aircraft was coined. The net result was the ability to respond to the pilot's commands as would an aircraft of widely different aerodynamic and geometric features. The degree of sophistication has increased to where the aircraft can "simulate" a full mission scenario with advanced guidance, helmet mounted displays, autonomous systems to relieve pilot workload, along with computers programmed to model the dynamics of different type aircraft. These capabilities provide to a greater degree a more versatile in-flight simulator, that years ago with vacuum tube circuitry, one could only dream about.

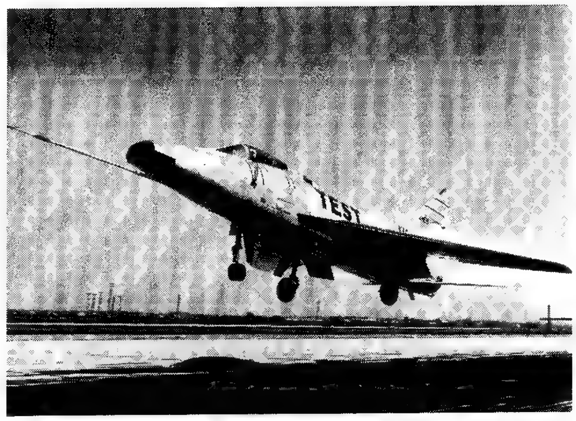
Over the last 50 years Ames has developed and used over 12 aircraft with varying amounts of in-flight simulation capability. It is beyond the scope of this paper to review each of these in detail. Emphasis is placed on those vehicles that were dedicated to conduct VSC research using visiting pilots to refine handling qualities requirements. Interesting highlights of flight test programs are reviewed with primary emphasis placed on challenges encountered and remaining for the various research aircraft used.



VSC studies in the USA started using a Grumman F6F-3 propeller-driven, low-mid wing, single-place, carrier based fighter aircraft in 1947 (figure 13). The need for developing a VSC capability originated because a "new" carrier based aircraft, a Ryan FR-1 Fireball had questionable "effective dihedral" (roll due to sideslip) such that in the landing configuration, it was not possible to pick up a low wing by normal use of the rudder. A "brute force" approach was taken to answer the question by building and flight testing three aircraft, with 7°, 9° and 11° of geometric dihedral. An Ames engineer viewing the three modified FR-1 aircraft side-by-side on the flight ramp said "there must be a better way"-the result was the variable stability F6F aircraft (ref 36). In addition to its use to establish more credible lateral/directional handling qualities specifications, it served to help develop the lateral/directional stability and control systems for a variety of advanced aircraft including the Douglas X-3, Martin B-57, Convair B-58, Lockheed F-104, Vought F8V, Grumman F-11F, and Cessna T-37 aircraft.

As tests continued, modifications were made to improve versatility as a research tool. After several years, directional (rudder) control was added to broaden studies of lateral/directional characteristics. In addition, the effects of atmospheric turbulence was added by driving the ailerons and rudder with a mechanical random input. This provided "consistent" approximations of rough air, which helped the pilot in evaluating dynamic response characteristics. A complex differential-control linkage and a remote driven aerodynamic lab system was developed to prevent the pilot from detecting variable stability inputs. This was not completely successful and remained a challenge over the life time of F6F use. Since there was no safety pilot to take over control in the event of a control malfunction, studies of landing approach characteristics had to be conducted at altitude.

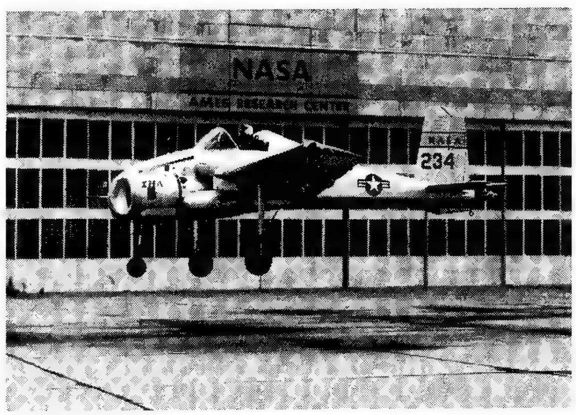




The results obtained from the F6F-3 tests showed that the VSC concept had tremendous potential to provide solutions to handling qualities problems of current and future aircraft designs. The challenge to improve the F6F VSC concept for higher performance aircraft led to the modification of a North American (NAA) F-86A swept wing fighter (ref.37) in 1955.(fig 14.) Initially, only a limited (rudder only) variable stability system was used. This provided not only a more modern cockpit with an improved mechanical (boosted) control system, but also allowed research to be extended to much higher speeds and higher values of Dutch roll frequency. The rudder servo system installed in the F-86A was an electro-hydraulic type that provided variations in yawing-movement derivatives including Cnp, Cnr, and Cn§a. Tests flight conditions covered speed ranges from 0.60 to 0.80 Mach No., and 10,000 to 35,000 ft.. Characteristics of a wide variety of advanced aircraft were simulated (ref.35).

The next challenge was to add variable lateral control features (1958) using an F-86E (ref. 38) which had an all-movable "flying tail". This provided an improvement in simulating rough air in that combinations of stabilizer and symmetrical aileron deflections gave lift components which felt more realistic. The overall system provided a capability to investigate a larger range of lateral/directional dynamics than available with the F6F-3. Results with this more representative fighter aircraft (ref-38) indicated that more lenient damping requirements were acceptable for the emergency (dampers-failed) condition.

Another step-up in VSC capability used a F-100C aircraft, (1960), providing three degree-of-rotary freedom and one translational (vertical) axis in a fighter aircraft designed for super sonic flight. (fig. 15) The pitch variable stability system required special control authority limits to insure flight safety concerns in use of the all-moving horizontal tail. The primary challenge was to design the system such that if the pilot selected a high gain setting, the control authority was reduced and vise-versa. Similar to previous installations, the pilot control inputs were introduced "fly-by-wire" fashion in a response feedback VSC system to drive the hydraulic valves for the control system actuators. The servo amplifiers were 400-Hz units which through a phase relationship governed the signs of the response feedback gains. The challenge to maintain this electrical system was so overwhelming that very little VSC flight research was achieved with this aircraft. A notable exception was a control sensitivity study for an "unknown" very high performance aircraft, which later proved to be the Lockheed SR-71 Mach 3 design. The sole reported research (ref- 39) was an evaluation of the use of DLC for in-flight refueling, which had proved to be demanding for the F100. The DLC capability was achieved by a blend of symmetrical aileron deflection and horizontal tail deflection. The DLC use showed a 20 percent improvement in reducing vertical error.



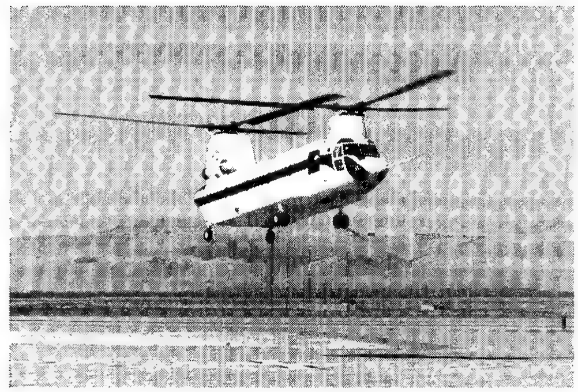
The first VTOL aircraft used in VSC research studies was the Bell X-14A (1960), a single place (open cockpit) twin engine vehicle using a deflected jet principle (fig.16). Two turbojet GE YJ85 engines located forward in the fuselage and a moveable cascade thrust diverter system provided VTOL capability. Control in hover was obtained from reaction jets located at the wing tips and tail. To provide VSC, additional electric servo-driven reaction nozzles were to which provide variations in rotary damping and control power using a response-feedback technique. The pilot could set the magnitude and sign of various input signals in flight. An error detection circuit was included in the VSC electronics to monitor signals commanding the servomotors to avoid erroneous reaction nozzle positions.

Control power and damping characteristics were evaluated in hover to establish boundaries between satisfactory, unsatis-factory, and unacceptable regions to aid design of future VTOL concepts. One of the first challenge was to eliminate inherent pitch/yaw coupling caused by gyroscopic torque of the X-14 co-rotating jet engines. In addition, for specialized tests, a hydraulically powered vane was mounted in the exhaust flow to provide a fourth-degree-of freedom-lateral translational control. Finally, after about 10 years, a model-following system was added to allow evaluation of attitude stabilized control modes.

The X-14 in-flight simulator was a prolific source of VTOL research results spanning over 20 years of test flight operation. Along the way, it was involved in a number of mishaps including dual engine flame-out in landing approach, ingestion of grass turf in hover, and lift off to hover without bleed air for the reaction nozzles. Over two dozen test pilots flew a variety of missions ranging from pre check out for hover of the British P1127 (Harrier) to simulated lunar landing profiles flown by Neil Armstrong. It provided for the first time, a more accurate definition of pitch, roll, and yaw hover control and rotary damping requirements in a realistic environment of jet exhaust ground effects. Comparison of in-flight and ground based simulation results indicated that pilots were willing to accept smaller control power values in-flight when hovering out of ground effect.

In summing up, there were limitations inherent in the X-14 powered lift concept which limited its versatility as a research tool. First, tests to define control criteria for STOL operation was not feasible because of unsteady aircraft behavior at transition flight speeds (60 knots) due to outward flow of the exhaust gases when the thrust vectoring vanes were partially deflected. Another was a safety issue associated with the need to fly close to the ground in hover. The X-14 was normally operated at a hover altitude of 12-15 ft.; high enough to avoid hot gas ingestion and low enough to be able to survive an engine failure. For various reasons, loss of lateral control resulted in "hard" landings where the pilot was unable to completely eliminated lateral drift before ground contact occurred. Finally, accurate definition of minimum acceptable control boundaries (P.R. 6 1/2) for landing is traditionally difficult because of the potential loss of flight path control and tests are usually made at altitude. For VTOL aircraft, tests must be made close to the ground such that translational velocities are apparent to the pilot. The ability to safely conduct in-flight simulation tests in hover remains a challenge particularly for single place aircraft.

Research on handling qualities criteria for rotorcraft using helicopter in-flight simulation started at Ames in 1977. A CH-47B (fig. 17) helicopter equipped with full-authority, electro-hydraulic actuators in each of the four control axes and with motions transmitted to the flight control system through rotary clutches (ref. 40). In-line triply-redundant, digital control rate monitors were set to disengage the research system when-ever excessive control rates were commanded for safety purposes. In the event of a failure to disengage, the clutches could be slipped by the safety pilot. The research system was qualified for use up to 120 knots and for hover operation to touchdown.



The flight experiments conducted made extensive use of the explicit model-following control system designed for near-hover maneuvering. The effects of high-order dynamics on the bandwidth of helicopter flight control systems was investigated which included control and display law design and landing qualities studies. These investigations sought design goals and handling qualities issues associated with the symbol drive laws for hovering displays such as that used in the AH-64 Apache Pilot Night Vision System, and validated advanced, integrated control-and-display laws for blind vertical landings as applied to a VTOL fighter.

The CH-47B proved to be a versatile research tool with 450 research hours and was flown by many visiting pilots for 10 years. It had limitations, however that prevented its use for studies of certain critical areas such as high-bandwidth flight control and agility/maneuverability due to system delays in the digital flight control system and by potential destabilization of the rotor modes. In addition, the actuator rate monitors limited aggressive maneuvering and nuisance disengagements were common. Finally, the basic CH-47B airframe had drag characteristics which limited its ability to correctly simulate other VTOL concepts such as a tilt wing.

The use of in-flight simulation is continuing at NASA Ames using a UH-60A Black Hawk helicopter (fig. 18) described in

detail in Session V (b). The research system includes a full-authority, programmable, fault-tolerant/fail-safe, fly-by-wire flight control system and a real-time obstacle detection and avoidance system which will generate low- altitude guidance commands to the pilot on a wide field-of-view, color helmet-mounted display. Judging from current funding and flight program restrictions, there appears to be the end of an era for in-flight simulation at Ames. In part, this is a natural consequence of advancement in other testing technologies and the fact that VSC aircraft at Ames had fulfilled a highly specialized role in flight testing in a timely matter. They were unique in capability to define handling qualities/pilot rated boundaries and for their use for researching problem areas not anticipated when first developed. Their strong virtue from the pilots' standpoint was that they flew like real aircraft, in contrast to the make-believe imitations encountered in early ground based simulators.

CONCLUDING REMARKS

A brief historical review of the development and use of piloted research simulators at NASA Ames has shown that the specific task and related maneuvering requirements dictated the level of motion system sophistication required. When conducting tests to determine selection of carrier approach speeds with an aircraft that had satisfactory stability and control characteristics, a fixed base simulator was adequate. When evaluating flight path control for a vehicle with stability and control limitations such as the space shuttle, a very sophisticated all axes motion system is required to achieve meaningful results. The type and amount of motion needed to evaluate aircraft control also depends on the task. For example, in a VTOL hover task, initial angular control response is sufficient. For tasks where translational positioning is critical such as engine failure during take off, a large amount of lateral translation is required. Experience has indicated that in a trade off with all six degrees of freedom, vertical motion should not be compromised. The degree of motion system sophistication is also influenced by the type of visual display. In general, TV displays were adequate only when limited maneuvering was required. CIG displays with a wide field of view are required to define control requirements for translational tasks.

In-flight simulation played a timely role in defining critical handling qualities criteria primarily influenced by dynamic (oscillatory) response characteristics. Continued use will be in highly specialized roles such as the need to more accurately define criteria for coupled guidance, control, and display systems for real mission tasks that heavily involve pilot/machine interface. Understanding (interpreting) human functioning and interaction in the human/simulator system remains an important challenge for continuing and future piloted simulation research.

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SIMULATED VISUAL SCENES - WHICH ARE THE CRITICAL CUES?

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SUMMARY

Research has shown that pilots can extract information from relatively impoverished visual scenes. However, performance of a variety of simulated flight tasks improves with greater scene complexity. Simulator visual systems cannot replicate the real world. Further, it is not possible to optimise visual system performance in all areas simultaneously. Some improvements in flight simulator visual cueing will come inevitably, as technology advances. Others present a research challenge, particularly where the likely effects of missing, contradictory or distorted information are not fully understood. These include:

> The luminance dynamic range of the display; this is far less than that encountered in reality. Relative luminances between objects cannot be maintained. Luminance variations with range will therefore be distorted. Maintaining accurate colour ratios at low luminances is also difficult. By careful mapping, detection ranges could be adjusted to be nominally accurate under specific conditions but not continuously accurate. The implications need to be considered carefully.

> The simulation of night scenes, with some illuminated areas may require the simultaneous mixing of 2 or 3 models in the same scene, creating unusual data base management demands. This requires further investigation.

> Distance judgments may be observed to be inaccurate in the simulator. To prevent this leading to degraded simulator performance and deficiencies in training it may be possible to compensate for the absence of some cues by enhancing the effect of others. Further investigation is required to establish whether such compensation is truly possible, to what degree it enhances simulator effectiveness and to identify associated costs.

1. INTRODUCTION

"Critical" cues are defined here as those necessary and sufficient to enable training to take place in the simulator. Training may be a matter of practising existing skills or learning new skills for transfer to the real world. In the case of aircraft simulation these may be handling skills for the novice or tactical/mission skills for more experienced pilots. In this paper we are concerned only with aircraft handling skills which depend on the use of external visual information, not those which rely on utilisation of instrument displays (either head up or head down).

This paper considers the question of how we can define which cues are critical to the success of a simulated visual scene.

A logical approach may be specified as follows:

> Identify visual judgments pilots need to make when performing essential tasks.

> Identify links to real world characteristics which supply the information needed to make these judgments. (This requires an understanding of the principles of how such judgments are made and the perceptual mechanisms which underpin the visual system response. It would be necessary to take into account research carried out into both static and dynamic visual perception).

> Review current simulator capabilities and limitations as these will constrain present cue representation and the ability to match specific cues to specific task requirements. These also represent areas for improvement/research.

The apparent simplicity of this approach, masks a number of inherent complications. There are gaps in our current knowledge, as reflected in our incomplete understanding of human perceptual processes, of how real world information is used and the consequences of a reduced fidelity environment in the simulator.

2. IDENTIFICATION OF VISUAL JUDGMENTS

The intention would be to encompass all the different types of judgment pilots make while flying.

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2.1 Subjective Approach

One option is to ask pilots themselves about the judgments they need to make when performing essential tasks within a specified environment. They could even be asked to identify the cues they would use to help them make these judgments. This approach is attractive because it could be used to take into account the needs of the user in deriving a visual database specification. For each mission, or part of a mission, an analysis can be carried out, following a structured approach; for example task analysis based on a knowledge elicitation exercise carried out with experienced pilots and instructors.

Caution should be exercised as it is by no means certain that even "expert" aviators are capable of identifying all aspects of visual cueing that they use. This is because the skills being exercised, such as judging distances involve perceptual processes which operate at an unconscious level. These are in fact universal human skills which have become adapted to the flight environment, in which orientation with respect to external objects can be much more varied than in a conventional earthbound setting. The adaptation process is mediated through experiential learning, it is not explicitly taught and the operation of such skills is not consciously monitored.

2.2 Objective Approach

An alternative to conducting interviews with individual pilots is to refer to previous findings in the research literature. When moving through the terrain, in good visibility, pilots have been shown to use visual cues to:

- identify terrain features
- determine rate and direction of movement
- determine rate of closure
- determine orientation
- determine distance from obstacles
- determine height above terrain

The characteristics associated with appropriate sources of cueing information may be predictable in some cases but the actual environmental cue used will depend on the task and the specific visual environment. Further, individual pilots may choose idiosyncratic features within that visual environment to aid them. There may be a number of possible cues and an individual pilot is not necessarily dependent on any particular one, nor do they all need to be present. This adds to the difficulty of determining which cues are the essential ones.

3. SOURCES OF INFORMATION AND VISUAL PERCEPTUAL MECHANISMS

Pilots have been shown to be able to extract information, even from relatively impoverished visual scenes, for example detecting changes in speed and altitude from a simple grid pattern on a flat terrain surface (Ref 1). However, performance of a variety of simulated flight tasks improves with greater complexity and the addition of specific features. The most highly rated scenes are those representing discontinuous distributions, including regions with "considerable vertical and horizontal extent." Scenes such as this are typical of the natural world e.g. groups of trees and/or large buildings separated by fairly large spaces. The work of Lintern (Ref 2), indicates that subjects trained with a simplified scene never subsequently achieve the same high level of performance as those trained with a relatively detailed landscape. This suggests that a realistic visual environment is important, at least for the initial acquisition of appropriate skills. Caution should therefore be exercised in deciding what may be omitted.

Many aspects of the visual environment, both static and dynamic, contain potential information. For example, static cues, such as texture gradients, colour contrasts and luminance contrasts, may be used to identify objects and terrain features (Ref 3). Equally, dynamic cues, such as motion parallax and optic flow can fulfil the same function. The optic flow pattern (Ref 4) can be used to estimate the direction, rate of self motion and orientation of a vehicle

For distance and closure information, again both static and dynamic cues may be of importance. As an illustration of the complexity involved in such perceptual processes some of the mechanisms of depth/distance perception are discussed in more detail below. Static cues include both monocular phenomena (such as object size and surface texture) and also binocular cues (such as convergence and stereopsis). Motion parallax and texture changes provide important dynamic distance cues.

3.1 Static Depth/Distance Cues - Monocular

Object size: Absolute distance judgments are probably dependent on size and perspective i.e. relative size on the retina. Familiarity with the object and its likely size is important. Pilots would, or at least could, be consciously aware of using this cue. Anecdotal evidence suggests that Army helicopter pilots make use of trees to help them visualise long range distance. They have a notion of the height of a "standard tree." This can lead to errors if appearances are deceptive, for example if there are stunted trees. However, the level of detail visible will also vary with range and can be used to confirm an initial distance judgment. The smallest area that can be discriminated as distinct from its background varies considerably with range. At 20 ft, an insulator on one of the crossbars of a telegraph pole may be discernible. At 4000 ft the observer would be looking for the whole pole.

Texture: Texture gradient provides information on the relative distance of locations on a surface and on the shape and slant of the surface itself. Abrupt change in texture indicates separate objects.

3.2 Static Depth/Distance cues - Binocular

Convergence: The closer an object of interest is to an observer the more the direction of gaze of both eyes will be turned inwards, towards the nose, i.e. the greater the degree of convergence of the eyes. Cues to distance are derived from feedback on the degree of contraction in the relevant controlling muscles of the eyes. At the same time the lens in each eye accommodates by becoming thicker in order to ensure the image is in focus. The degree of accommodation can also be interpreted as a cue to distance.

Stereopsis: Due to the horizontal separation between the two eyes, each sees a slightly different view of the external world. There is overlap between the two visual fields which provides stereoscopic information. If the eyes are focused on an object, the image of this object is said to fall on corresponding points on each retina. At the same time the images of an object which is either nearer or more distant will fall on disparate points on the two retinas. The amount of disparity will depend on the distance between the non fixated object and the fixation point. A fairly precise appreciation of relative distances and depth relationships between objects can be derived from the degree of retinal disparity present.

Binocular cues to distance will only work at relatively short distances, say within 30 ft of the observer with stereopsis providing information out to longer distances than convergence (Ref 5).

3.3 Dynamic Cues to Depth/Distance

Motion parallax: This allows perception and judgment of distance based on differential rates of displacement of retinal projections corresponding to objects. Assuming that an observer is moving through the environment, those static objects outside the direction of movement which are closer to the observer move more quickly over the retina than do more distant objects. This is an important cue to the relative distance of objects.

Size: For objects in or near the direction of movement approach causes an increase in size at the retina and moving away causes a decrease in size. Rate of change of the monocular depth cue of size provides range and speed information as the greater the distance from the eye the slower the retinal velocity.

Texture: Dynamic changes in the texture density of objects also indicates movement in depth. Small scale variations in terrain contour can be very salient (Ref 1). It is suggested that optical flow discontinuities may play an important role in delineating boundaries between surfaces.

Which perceptual mechanism is of greatest importance in providing the observer with information may vary according to circumstances. For example, at slow speeds motion parallax information is weak. Distance judgments would depend mostly on size, relative size and stereopsis. At longer range, size is more sensitive as a range discriminator, than stereopsis. There is however a cross over at a range of about 10m when range discernibility due to stereopsis becomes more sensitive than that of size (Ref 5, Ref 6).

Assuming cue requirements can be established these will need to be translated into simulator requirements. Some critical issues which limit the simulator's performance need to be considered. These are discussed in section 4 below.

4. SIMULATOR CONSIDERATIONS

A number of factors influence the simulator's ability to represent visual cues adequately. These include:

- level of scene detail
- display brightness
- field of view (FOV)
- resolution
- ambient light levels
- flicker (display refresh rate)
- smoothness of apparent motion
- contrast brightness
  - colour
- accommodation micropsia (Ref 7, Ref 8)
- lack of true stereopsis

Simulator visual systems cannot replicate the real world. Further, it is not possible to optimise visual system performance in all areas simultaneously. Compromises need to be made but should be such that the simulator configuration will represent important cues well. Task analysis and knowledge elicitation exercises can help to identify some of the important cues, on a task relevant basis. However task analysis does not yield the effects of missing, contradictory or distorted information which may be encountered in the simulator. In these cases reference has to be made to previous research findings, to consider the potential deleterious effects on aircrew performance, workload and behaviour.

The factors listed above affect: perceived realism and visual search behaviour (Ref 9) range of detection, recognition and identification (Ref 9, Ref 10, Ref 11), reaction times (Ref 11) and height/speed judgments (Ref 12). For example object recognition is more difficult at low levels of illumination and visual acuity is a function of display luminance, contrast, resolution and level of scene detail. Limitations in display resolution and

update rates will affect the quality of smooth apparent motion and therefore reduce the effectiveness of motion parallax as a cue to relative distances (Ref 12).

Apart from scene detail, which depends on the simulator's image generation capabilities these issues are related to the display and are largely interdependent. For example increasing the FOV of a visual channel degrades resolution, brightness and contrast. Improvements in display brightness, fov, resolution, ambient light levels, flicker and smoothness of apparent motion will be seen as visual systems (Computer Image Generators, (CIGs) and displays) develop. On the other hand the ability to provide appropriate contrast, to counteract the influence of accommodation micropsia and to provide true stereopsis are areas which require research to establish if and how improvements would be possible. Each of these three areas will be considered in turn.

4.1 Contrast

Contrast, both brightness and colour contrasts, affect; distance judgements at all ranges, the discernibility of cues, realism and the observed quality of the image (Ref 13).

One major problem is that the luminance dynamic range of the display device is far less than that encountered in reality. Hence the computed luminances need to be mapped onto a display luminance which has a smaller dynamic range. This reduction in dynamic range means that relative luminances between objects cannot be maintained in the simulator so that luminance variations with range will be distorted and, more seriously, detection ranges will be in error. By careful mapping, taking into account the luminance perception of the user and the spatial frequencies of the object (Ref 13), detection ranges can be adjusted to be nominally accurate under specific conditions but not continuously accurate. Hence it may be important to designate conditions in the exercise when accuracy is paramount and accept discrepancies outside these conditions.

Colour adds another problem to that above: the mapping also has to allow the tracking of colour from high luminance to low luminance in the daylight scene. The problem is to maintain accurate colour ratios at low luminances and maintain realistic differentiation of cues from the background, although the human ability to distinguish colour diminishes as the size of objects reduces. There is yet another added complication in that the user often thinks that computer generated scenes are more realistic when the scene is actually richer in colour than in real life (Ref 14). Which then is most applicable to training - accurate representation or what the user thinks is more realistic?

Night scenes are generally monochrome to the viewer, apart from lights and illuminated areas. The relative luminance of surfaces will change in transitioning from daylight to night (Ref 14) requiring different visual colour and contrast models (ie. the polygon shape will tend to remain the same but different contrasts are required). If there are illuminated areas in the night scene then for a particular area a different, daylight model may be required. This is further complicated by Night Vision Goggle (NVG) viewing when relative luminances will again change. Examples from Howard and Burnidge (Ref 14) are: red sandstone appears lighter than dry boulders in daylight but appears darker than dry boulders in moonlight; green grass appears darker than gravel in daylight and moonlight but lighter when using NVGs. Yet another contrast model will be required. Thus there may be a simultaneous mixture of 2 or 3 models in the same scene requiring a form of data base management based on conditions, rather than the conventional reliance on position and heading alone. The relative discrimination between these surfaces will also be a function of the display and human observer (Ref 13) and emphasises the contrast mapping problem mentioned earlier.

NVGs require stringent controls on lighting in the simulator cockpit, for example reflections should be kept down to a minimum, as the goggles are sensitive to any stray light, including non visible light. Consideration of such factors as non visible light do not normally concern display manufacturers. If NVGs are to be used in the simulator there may be increased expense in selecting suitable displays.

4.2 Accommodation Micropsia

As already stated absolute distance judgments are probably dependent on object size and also on perspective i.e. relative size on the retina. However this information can be deceptive. When the accommodation and convergence of the eyes are increased i.e. when there is a move inwards to focus on a position closer to the observer this has an effect on the apparent size of other objects in the visual scene. An object positioned beyond the point of focus appears to be reduced in size (Ref 8). This phenomenon is commonly known as accommodation micropsia.

The accommodation micropsia phenomenon is not however simply due to an error in size at the retina (Ref 7). The change in size of retinal image attributable to accommodation is virtually negligible compared to the subjective perceived reduction in object size. The underlying mechanisms for this phenomenon are not understood. It seems that there is some relationship between distance judgments and visual accommodation distance but it is not a simple one.

When not viewing the scene directly (Ref 8), as in a simulator, with the image presented through a display system and at a fixed distance it is known that there are likely to be misjudgments of distance. Whether this is in part attributable to the observer's accommodative state is not known. The effect on the eyes accommodation when confronted with a simulator visual system with its fixed image distance has not been measured. It is known that accommodation tends to drift towards a natural resting position unless forced to do otherwise by the acuity demands of the visual scene. This resting position varies from one individual to another but tends to be at a fairly close distance (approx. 1 metre for the normal eye). This response would be expected to real world scenes lacking in information for example at night or in fog, leading to so called "empty field myopia." Distance judgments would be likely to be affected. A simulator scene lacking in texture might produce the same effect. The fixed distance of the simulated image means a lack of demand for changes in accommodation, whatever the level of scene detail. This might itself produce biased distance judgments in a similar fashion.

What is the solution? A simple adjustment to image magnification would presumably not be sufficient to correct for accommodation micropsia as the size of the image at the retina seems not to be directly linked to judgments of object size. An alternative would be to try to overwhelm the false size impression by providing stronger alternative cues in the form of scene detail and texture. Another option is to have the image distance of the display device match that of the observed object as nearly as possible; requiring a collimated display for long distance judgements and non-collimated for short distance judgements.

4.3 Stereopsis

Lack of true stereopsis has effects on range, height and speed judgements. These are more critical in rotary wing flight than for fixed wing due to the closer ranges involved and the slower flight speeds (Ref 5, Ref 15). As rotary wing flight and its simulation requirements are very different from those of fixed wing it is perhaps necessary to consider some of the more relevant aspects of these differences in greater detail.

5. ROTARY WING AIRCRAFT - SPECIAL CONSIDERATIONS

Rotary wing aircraft possess a number of unique characteristics; such as the range of manoeuvres they carry out. These include stationary hover, short accurate stop/start manoeuvres and flying slowly, at low level, in and around obstacles. These place unique demands on the pilot's perceptual abilities and therefore on any attempt to simulate the pilot's perceptual environment.

NOE flight, in which the pilot operates close to the ground, is particularly demanding. This can mean flying in and among buildings, trees, bushes and other terrain features. This allows the pilot to take advantage of both natural and manmade objects to screen him from enemy detection systems, whether visual, optical or electronic. Airspeed and altitude will vary depending on terrain, weather, ambient light and presence/location of threats but generally the flight will be low (at 20 ft or less) and slow (< 40 kts) (Ref 16).

The margin for error is very small. The pilot therefore needs to have a good awareness of the vehicle's physical dimensions and performance capabilities and to be continuously and accurately estimating present and projected position relative to the immediate environment. There is high dependency on visual judgment to be able to avoid hazards at close proximity such as trees, wires etc. Specifically there is a need to be aware of current position relative to these, i.e. proximity, height and aspect relative to those which present the greatest potential danger to the aircraft.

Distance judgments are of paramount importance. At the slow speeds typical of NOE flying, these are mainly based on size, relative size and stereopsis (retinal disparity). Information from motion parallax is weak (Ref 5, Ref 15). This contrasts with low level fixed wing flight in which, owing to the high speeds involved motion parallax is a strong cue and stereopsis is probably not important as objects remain in the stereoscopic zone for only a short time. For the helicopter pilot close range judgments are probably enhanced by scene detail and texture. Approach speed judgements, i.e. judgments of motion in depth rely on rate of change of size and may use rate of change in retinal disparity.

6. ROTARY WING SIMULATION - SPECIAL CONSIDERATIONS

The above considerations present a considerable challenge to achieving appropriate simulation for rotary wing aircraft. Close range distance judgments are known to be difficult in the simulator at the slow speeds generally required by helicopter NOE flying. At slower speeds human sensitivity to motion parallax is reduced. Display resolution limitations mean that even less stimulation is available to this visual mechanism in the simulator. In the real world stereopsis may compensate for the deficiency. The judgment of distances of less than 30 ft. probably normally relies on some stereopsis information but this is not represented in conventional simulators. Distance and approach speed judgments are therefore likely to be degraded. The situation is made worse by the fixed distance of the image which provides a false stereopsis cue and which degrades size judgments.

It is probably not practical to provide suitable stereoscopic displays (Ref 15). It is not however acceptable that equipment limitations should present pilots with perceptual deficits which can lead to degraded performance in the simulator and deficiencies in training. As humans generally have a variety of perceptual mechanisms which can provide them with required information it may be possible to compensate for the absence of some cues by enhancing the effect of others. In this case, compensation for lack of motion parallax and stereopsis cues may be possible to some extent, by providing finer detail, as range reduces, to strengthen relative size and perspective cues (Ref 17). Relative size cues provide greater sensitivity than absolute size. Further investigation is required to establish whether such compensation is truly possible, to what degree it enhances simulator effectiveness and also to identify the associated costs.

There may however be undesirable consequences associated with this solution which requires the CIG to generate fine detail at close ranges. NOE flight, which typically involves rapid dashes for cover and moving above close terrain already tests the capabilities of the CIG and its data base management system. Rapid changes in the scene mean that the CIG needs to be able to switch its computing power quickly to show new detail as it comes into view. If the level of detail increases, the demands on data storage and computing power will rise. This will affect the iteration (update) rate of the computations. It is likely that this rate would have to slow down to prevent information being lost. This has serious implications because the iteration rate indirectly controls the display flicker rate and hence the quality and acceptability of the display. The iteration rate also affects the quality of the smooth motion: the higher the iteration rate, the smoother the motion. There is thus no simple solution as any changes made in one part of the simulation environment are likely to have ramifications for a number of others.

7. CONCLUSIONS.

The potential areas for improving visual cueing in flight simulators can be divided into two broad categories, those which can be accomplished through development, as the technology advances and those which present a research challenge.

Areas where development is likely to produce significant improvements in the future include:

increased	CIG detail
	field of view
	resolution
	display brightness
reduced	levels of flicker
enhanced	smooth motion

Research is needed in areas where the human responses to information, lack of information or contradictory information are not yet fully understood. The questions to be considered include:

whether short range judgements at slow speeds require compensation for lack of stereopsis information in the simulator; whether such compensation is possible and if so implications for both effectiveness and costs

effect of fixed image distance on accommodative state of the eyes and possibilities of compensation for accommodation micropsia

the matching of colours and contrasts for objects to be recognizable at specific ranges and possible tuning of the matching for specific tasks.

whether specific data bases may be required for specific tasks.

whether simultaneous mixture of contrast models is required for simulation of night time and/or NVG operations

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Visual scenes for battlefield helicopter operations: Evaluation of requirements and how to specify them.

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ABSTRACT

The structured specification and evaluation of simulated visual scenes for training pilots in tasks such as Battlefield Helicopter operations is required to ensure that cost-effective flight simulator training is being achieved. Historically this has been a difficult process because of a lack of consistent and prioritised descriptions of different visual flight activities within the intended training missions; limited evaluations of the contributions and relative importance of different scene features within appropriate operational scenes; and a lack of any structured way of collating and presenting such information to those who specify and design visual scene databases for flight training simulators. A research programme funded by the UK Defence Research Agency was conducted in collaboration with Cranfield University, UK to address these challenges. Specific aims were to identify and prioritise visual flight activities in the context of a battlefield nap-of-the-earth (NoE) attack mission; to determine the relative importance of visual scene components (e.g. woods, farm buildings, roads, livestock) to the achievement of visual flight activities; and to assess the impact of removing or adding information to the scene upon the achievement of visual flight activities in a mission simulator. The purpose of the paper is twofold: firstly to describe the human factors procedures and techniques used to address these aims, and secondly to describe the proposed structure of a computer based relational database to integrate the results of the programme. Selected findings from the study are used to highlight the structure of the database.

1. INTRODUCTION

Simulation of Battlefield Helicopter operations can be a major contributor to training programmes and, with the provision of appropriate geographic scene databases, can also provide the capability to rehearse missions into previously unfamiliar areas. Battlefield Helicopter operations depend to a very large degree on interpreting the visual scene either directly or through Electro-Optical systems such as Night Vision Goggles (NVG) or Forward Looking Infra-Red (FLIR) sensor displays. It follows that the effectiveness of Helicopter simulators for battlefield operations will be critically dependent on the effectiveness of the simulation of appropriate visual scenes.

Despite continuing advances in the capabilities of real-time visual scene generation and display systems, current visual scenes provided for battlefield operations are, at best, disappointing and, more often, not able to provide adequate support for training, other than procedural activities where a visual scene is a background feature. This is partly because of limitations in current image generation and display systems, but mainly because of the lack of adequate reference data to assist with the specification, design and evaluation of visual scene systems for specific tasks.

It does not seem unreasonable to say that the design aim should be to achieve a <u>realistic</u> visual scene. However, it is currently not possible to achieve this aim, and it will probably never be totally possible. Attempts to increase realism are mostly beneficial to the performance of mission tasks, but the scene database designer will always have to make compromises in the representation of the real world and the all important details that are needed to perform a visual mission. In making these decisions the designer needs detailed information about the specific tasks to be simulated and which visual features are necessary for the successful performance of these tasks. Currently such information is very limited; it often does not relate to specific tasks, and there are no indications of the relative importance to the performance of a task of particular types of features or the individual visual elements that are present in a feature. The designer uses his skills and expertise to create appropriate visual scenes and the end result will often look quite good at initial acceptance, but, if it is not satisfactory, major changes would be long and costly to make at this stage Even if a visual scene database looks quite good it is very often found to be disappointingly inadequate in service, because the customers and the designers have not been able to identify and prioritise visual features that are important to the tasks that are to be simulated.

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The fundamental problems in specifying visual scene content for battlefield helicopter operations are

a. Lack of consistent and prioritised descriptions of the different Visual Flight activities, e.g. control of speed, height and attitude, that are parts of the main tasks within the missions that are to be simulated

b. Lack of evaluation in appropriate operational scenarios of the contributions and relative importance of different visual scene objects, textures, etc. to the success of the various Visual Flight activities

c. Lack of a structured way of presenting the information relevant to the previous two problems so that designers can identify and then apply relevant knowledge to the design of the overall visual system

In addition, current visual display systems fall short of the real world because

a. Display resolution is not as good as a pilot's eyes

b. Scene brightness and contrast are much less than normal daylight (although they can be appropriate for NVG operations)

c. Two-dimensional displays lead to compromises in presenting three-dimensional effects.

It is difficult to overcome these fundamental problems in a simple way Previous studies have either concentrated on understanding the contributions of simple visual scene components either in isolation or together with a 'manageable' number of other simple elements, or, in other cases, they have tried to summarise the requirements of pilots in a general descriptive document based on questionnaires and discussions (refs. 1-11) Both types of study have contributed significantly to the body of knowledge about visual scene elements and pilots requirements However they have not overcome the fundamental problems because purchasers and designers cannot readily extract and prioritise information relevant to particular operational tasks and Visual Flight activities One of the important features of this present study is the presentation of visual scene information in a framework of priorities for Visual Flight activities within particular mission tasks, and the development of a structured way of presenting the knowledge gained during the study.

One of the main problems in determining the relative importance of scene components in the performance of a flying task is finding out the effects on the task of removing a single component Pilots have experience of the effects of losing large numbers of scene components in operations over water, snow or sand, but much less experience of the effects of removing a few components from a richer scene In most cases a pilot will not have any experience of the effects of losing a single component and any comments will be subjective opinions, which probably will reflect the expected importance of the component without any real knowledge of how other scene components may alleviate the effects of the loss The effects of removing a component can only be identified by evaluating the effects of its removal in a simulation of the task.

Simulation evaluations of the influence of important scene components on mission task performance have been completed as part of this study programme (ref. 12), which has been conducted on behalf of the Defence Research Agency This paper is presented in two parts. In part one the evaluation procedures used to specify the minimum scene content requirements of visual simulation systems to support the training of NoE helicopter operations are reported. Part two describes a way of structuring the information so that is can be accessed readily by personnel involved in the design, evaluation and procurement of visual simulator systems.

2. EVALUATION PROCEDURES

The research objective was the development of a specification for the procurement of visual simulation systems to support the training and rehearsal of Nap-of-the-Earth flight in battlefield helicopters. The philosophy adopted was that the information contained in a visual simulation scene needed to be sufficient to support the student training requirements as specified by the instructor. Accordingly, the scene content needed to be sufficient to enable the demonstration of appropriate visual cueing strategies by instructors (e.g. backdrop technique) and subsequent rehearsal by students. The objective was investigated in three phases which will be described in the following sections.

2.1 Phase One: Preliminary studies.

In the first phase observational flights in battlefield helicopters and structured interviews with aircrew lead to the definition of the mission tasks; training goals and specification of a real world area to be modelled. A battlefield operation consisting of 8 mission tasks, which were slope landing, transition, tactical flight, spot turn, quickstop, missile firing, transit and low level navigation was chosen to represent a typical range of visual activities. The training goals were defined as precision hover, transition, low level manoeuvre and forward flight. The set of flight activities which needed to be mastered to achieve these tasks were the control of heading, track, ground position, attitude, height, speed, flight path, range; the avoidance of obstacles; rate of turn and knowledge of map position.

In addition, as part of this phase a set of 12 visual cueing strategies were identified, which were relevant to the achievement of the flight activities. These strategies were termed recognisable features; vertical backdrop; lateral backdrop; surface shading; natural texture; man-made object texture; perspective; streaming; ground rush; colour; line features; and the coincidence of objects.

2.2 Phase Two: Survey research

The preliminary research led to the development of a survey questionnaire to identify the relative importance of each flight activity to the performance of a given mission; the relative importance of each visual cueing strategy to the achievement of the eight flight activities; and the information in the real world scene used to support the implementation of each visual cueing strategy.

2.2.1 Questionnaire structure and content.

The questionnaire consisted of three sections which were semi-structured and designed for completion in the presence of the researcher following a 20 minute briefing. In the opening section participants were advised of the purpose of the exercise and requested to provide brief details of their flying experience (i.e. course attending or instructing; status; and flying hours). The purpose of section two was to determine the importance of the flight activities to the performance of each mission tasks. Pilots were provided with the mission task descriptions and requested to evaluate the importance of the flight control activities to the overall performance of each mission task. This evaluation was undertaken by each pilot for both poor and rich visual cueing environment. For the purposes of this study a poor cueing environment was defined as undulating terrain with poor visual cues (e.g. desert, NVG) and a rich visual environment as undulating terrain with rich visual cues (e.g. rural wooded countryside). Importance ratings were made using a 7 point Likert scale with descriptors 'irrelevant'; 'unimportant'; 'rather unimportant'; 'in between'; 'rather important'; 'important' and 'vital'.

Section three was designed to quantify the importance of each visual cueing strategy to the maintenance of each flight control activity. Similar to section 2 a separate evaluation was made for a poor and a rich visual environment and evaluations returned using the 7 point Likert scale.

In additional for each visual cue and flight control activity pilots were requested, where appropriate, to record examples of real world features which supported the use of a particular visual cue.

2.2.2 Procedure.

The questionnaire was pre-tested and approved by the point of contact at the Army Air Corps Centre Middle Wallop and Central Flying School, RAF Shawbury. Twenty-one rotary wing instructors from these squadrons took part in the survey (8 RAF and 13 Army Air Corps). Prior to completing the questionnaire participants were given a 20 minute briefing outlining the purpose of the study and describing how to record responses using the 7 point Likert scale. Pilots attended the briefing in groups of at least 5 and completed the form in the presence of the research team who were on hand to clarify completion procedures. The questionnaire took approximately 45 minutes to complete and was followed by a debriefing when pilots were invited to discuss their responses and to comment on the content and structure of the form.

2.2.3 Hierarchy construction.

Group means and standard deviations were calculated for each flight activity and visual cueing strategy. Separate hierarchies were derived for flight activities and visual cues and contained those items which received a group mean rating of between 5 and 7 (rather important, important or vital). Numerical rankings were assigned separately to each flight activity and visual cueing strategy to represent the relative position of the item within the relevant hierarchy. Tied rankings were assigned where identical mean ratings of importance were achieved for two or more items. As an example of this hierarchical organisation Table 1 summarises the relative importance of the visual cueing strategies to the 11 flight activities investigated.

Information derived from both hierarchies and pilot comments was used to define the parameter set of visual cueing strategies, features and elements to be manipulated during the flight simulation studies conducted in phase three.

2.3 Phase three: Flight simulation studies.

Two flight simulation studies were conducted to assess the impact upon pilot performance workload and perceived scene content sufficiency of removing or adding information to a computer generated operational scene. The facilities, parameter sets and methodologies applied during each study will be described in the following sections.

2.3.1 Simulation facilities.

Both trials used Defence Research Agency flight simulation facilities. In the first trial the facility used comprised a single seat attack helicopter cockpit with 200 degree horizontal field of view and 40 degree vertical field of view presented on 5 monitors mounted on a 3 degree of freedom (pitch, roll and heave motion platform). The visual simulation was presented using Silicon Graphics Reality Engines (SGRE) and was based upon a rich visual cueing environment regularly used by the Army Air Corps Centre to train battlefield helicopter operations. The second simulation trial used a single seat helicopter cockpit with 140 degree horizontal field of view and 48 degree vertical field of view mounted on a 5 degrees of freedom (pitch, roll, heave, sway, roll, yaw) motion platform. Differences in the visual simulation facilities meant that the scene database for manipulation during study 2 needed to be translated from SGRE to a Thomson Link-Miles IMAGE 600PT. This process was not purely a physical one, e.g. ground and surface texture patterns needed to be selected from the IMAGE texture pattern libraries to match the granularity and detail of those presented using SGRE. The extent to which this process produced a baseline IMAGE 600PT database which conveyed the same

Table 1: Relevance of Visual Cueing strategies to Visual Flight activities.

Key: Very relevant (dark shading) = Very relevant; Relevant (grid shading) = Relevant; blank = Irrelevant

Visual Flight Activities	Recognisable features	Vertical Backdrop	Lateral Backdrop	Surface shading	Natural texture	Man-made object texture	Perspective	Streaming	Ground rush	Colour	Line features	Coincidence of objects
Heading (Low speed)	Very relevant		Very relevant		Relevant	Relevant	Relevant	Relevant	Relevant		Very relevant	
Track (Forward flight)	Relevant							Very relevant	Relevant		Very relevant	
Ground position	Very relevant		Very relevant		Very relevant	Very relevant	Relevant				Very relevant	
Attitude		Very relevant		Relevant			Relevant	Relevant				
Height (Low speed)	Very relevant	Very relevant			Very relevant	Very relevant	Relevant					
Speed	Relevant							Very relevant	Very relevant			
Flight path (Forward flight)	Relevant			Relevant				Very relevant	Relevant			
Range	Very relevant				Very relevant	Very relevant	Very relevant			Relevant	Relevant	
Obstacle avoidance	Very relevant	Relevant	Relevant		Very relevant	Very relevant	Very relevant	Relevant			Relevant	
Rate of turn					Relevant	Relevant		Relevant			Relevant	
Map position	Very relevant				Relevant	Relevant				Relevant		Very relevant

visual cueing information as the SGRE database was tested to be satisfactory in a direct comparison on the same simulator.

2.3.2 Trial design and Parameter sets.

A description of the scene content parameters manipulated during each trial are summarised in Tables 2 and 3. The trial design and task sequences used each of the parametric scene changes within each task. A repeated measures design was used for both trials whereby eight rotary wing instructors performed a mission on four separate occasions. The mission consisted of eight tasks and a maximum of two parameters with two levels were manipulated in five of the task training areas. This resulted in a full factorial design and minimised the number of conditions to be flown by each pilot to four. To vary task order and scene familiarity effects, four start points along the mission were defined and the order of these four sequences varied between pilots.

2.3.3 Methodology.

The following subjective and objective measures were used to evaluate the sufficiency of the scene to support the performance of the mission tasks on four separate occasions.

i. Scene content sufficiency scale

ii. Debriefing questionnaire

iii. NASA Task Load Index workload rating scale

iv. Verbal commentary of the visual cueing strategies employed

v. Judgement of height and speed at random points during the mission

vi. Primary task performance

The debriefing questionnaire and accompanying scene content sufficiency scale was developed specifically for the trial. The questionnaire was divided into two sections which were completed for each evaluation task. In the first section a matrix of 12 visual cueing strategies and up to five flight activities presented. Pilots were requested to evaluate the sufficiency of the computer generated image scene to support the use of the visual cueing strategies to control each flight activity. Evaluations were made for each strategy and flight activity using the six point Scene Content Sufficiency scale presented in Figure 1. This scale consisted of two main categories labelled sufficient and insufficient which were further divided into 6 levels ranging from excellent (rating 1) to very poor (rating 6). Each level was described by the extent to which the scene was deficient and the potential impact of the deficiency upon the pilots visual cueing strategy (no deficiencies to major deficiencies) and the training requirement. Pilots were instructed to return a zero rating if a given strategy was not relevant to the achievement of a particular flight activity. In section two the visual cueing strategies were once again listed and pilots requested to describe the features in the computer generated image scene which were used to support the strategy.

Table 2. Scene content parameters manipulated during simulation trial 1.

Task Area	Parameter title	Description
Slope Landing	Rotor Downwash	Cone projecting from the base of the aircraft
	Surface shading	Directional source of light on the ground surface enhancing ridgelines
NoE tactical flight	Fogging	Distance of 6km.
	Outer tree layer	Line of trees presented 30 feet from the main wood block and modelled as a two dimensional surface with transparency between tree trunks and foliage.
Spot turn	Outer tree layer	As per NoE area
	Known size objects	Tractor and oak tree placed near entrance to confined area. Two tractors placed inside area.
Quickstop	Shading	As per slope landing area
	Known size objects	Livestock, farm machinery, stationary road vehicle.
Missile Firing	Positional cues	Foliage projecting horizontally from the outer tree layer
	Outer tree layer	As per the spot turn area.

Table 3. Scene content parameters manipulated during simulation trial 2

Task Area	Parameter title	Description
Slope Landing	Wood texture detail	Presentation of phototexture patterning on the sides of woods.
	Line features	Tractor tracks
NoE tactical flight	Wood texture detail	As per slope landing area
	Outer tree layer	Row of individually modelled three dimensional trees, spaced 70m apart and 30m from the main wood block & modelled one third the height of the main wood block.
Spot turn	Outer tree layer	As per NoE tactical flight
	Positioning cues	Three dimensional unique trees placed against the wood block.
Quickstop	Line features	Tractor tracks as per slope landing area
	Objects with vertical extent	Hay bales and bushes.
Missile Firing	Outer tree layer	Individual line of trees against wood block with height extending beyond background block.
	Unique canopy features	Solid triangular blocks placed on the surface of the rear wood block canopy.

SUFFICIENT Scene content is sufficient to exercise the relevant Visual Cueing Strategies (VCS's) to support the training of the flight activity or task objective.	***Excellent***	**No Deficiencies** Scene content contains all the information required to exercise relevant VCS's to achieve the task training requirement.	**1**
	Very Good	**Some Deficiencies**, but not in the primary visual features required to exercise relevant VCS's to achieve the training requirement.	**2**
	Good	**Some Deficiencies** in primary visual features required to exercise relevant VCS's but task training requirement remains achievable.	**3**
INSUFFICIENT Scene content is insufficient to exercise the relevant Visual Cueing Strategies to support the training of the flight activity or task objective.	***Fair***	**Deficiencies** in primary visual features required to exercise relevant VCS's. Task could be achieved by the trainee with a significant amount of additional effort and skill.	**4**
	Poor	**Major deficiencies** in the primary visual features required to exercise relevant VCS's. Task could only be achieved by the trainee through the use of unrepresentative VCS's which would be unacceptable for training.	**5**
	Very Poor	**Major deficiencies** in the visual features. Task is not achievable.	**6**

Figure 1. Scene content sufficiency scale

2.3.4 Procedure.

Eight rotary wing instructors from the Army Air Corps Training centre at Middle Wallop and the Central flying school at RAF Shawbury took part in the trial. Six of the eight instructors took part in both simulation studies. On arrival pilots were briefed on the purpose of the trial, handling of the simulation facilities, safety procedures and trials design, methodology and procedures. A video recording taken of the outside world whilst flying the mission in the real world was presented to the pilots to allow practice in the use of the evaluation procedures. Pilots were then randomly assigned to one of two groups. In group one the sequence order was 1,3,2,4 and in group two 2,4,1,3. Each pilot was given a 30 minute practice session during which he became familiarised with the handling of the simulation and the mission route. One mission sequence was flown during a 30 minute continuous sortie. Navigational information was provided by a hand held map and complemented by verbal directions from the trials team who were able to interrogate a 'God-eye' view of the database. This information was not provided for the low level and transit navigation tasks. At pre-specified points during each task flight parameters were data-logged to provide an indication of primary task performance and flight instruments were frozen and a judgement of height and

speed returned by the pilot. Throughout the task the pilot provided a verbal commentary of the types of strategies and scene content information used to achieve the task parameters. The scene content questionnaire and NASA workload scale were completed in the debriefing room following the completion of each sortie.

3. SPECIFICATION OF REQUIREMENTS

A wealth of information was collated from the activities described in part one of this paper and the briefest summary of results encompassed 30 pages of the technical report. This is lengthy and cumbersome to scene modellers who wish to make expedient decisions regarding the types of features which must be included in a visual simulation to support specific types of activities. Furthermore, as new knowledge is obtained and the Services wish to consider other missions the problem of information retrieval will be exacerbated. A solution to the data management problem is the construction of a relational database which incorporates structured descriptions of both the visual scene and the mission together with importance ratings. Information held in such a form can be incorporated in a way that is independent of particular mission scenarios so that knowledge can be applied directly to a much wider range of missions than that used for the simulation trials.

In addition to providing a structured format to hold data, such a database can also hold standard forms of objects for use in automatic database generation tools, together with references to standard object descriptions such as those used for the world wide Digital Land Mass Survey (DLMS) cultural features held in DFAD data files and those in distributed interactive simulation (DIS) standards.

In the second part of this paper a proposed form for a relational database to provide a structured dataset for mission based visual scenes is described and examples of its use are provided from a demonstration database containing some of the knowledge from the present programme.

3.1 Description of the structure for data

A general structure for a relational database to link visual scene characteristics and missions is presented in Figure 2. In describing components of a visual scene it is essential to have a hierarchy of features with consistent names.

3.1.1 Structure for visual scenes.
On the left hand side of the diagram the hierarchical structure for visual scenes is presented and consists of area, group features, objects and elements. The area is a portion of the database that contains a limited and specific set of features and objective e.g. an urban area contains houses, industrial units, roads but no farms or woodlands. Group features denote a collection of objects that by their arrangement form a recognisable feature, e.g. a farm site will have a farmhouse, yard, outbuildings, pond. Objects are the basic unit of a visual scene, which is a recognisable feature that can exist on its own, e.g. a tree, a house, a car, or a person. Finally, an element is an identifiable component of an 'object' but does not usually exist on its own e.g. a door or stone texture. An additional visual scene component covers environment aspects such as reduced visibility and wind. These are not objects but can influence visual cues available from the scene.

3.1.2 Mission structure.
A similar hierarchy can be produced to describe the components that make-up a mission and this is shown on the right of the diagram. A mission is a complete operational sortie with particular objectives, which can be described as a series of tasks such as hovering, nap of the earth flying, low speed manoeuvring and within each task there are a number of visual flight activities such as height control, ground position control, attitude control etc.

3.1.3 Linkage.
The general link between the mission factors and the visual scene occurs at the level of visual flight activities where there are a set of visual cueing strategies that link visual flight activities directly to elements and objects in

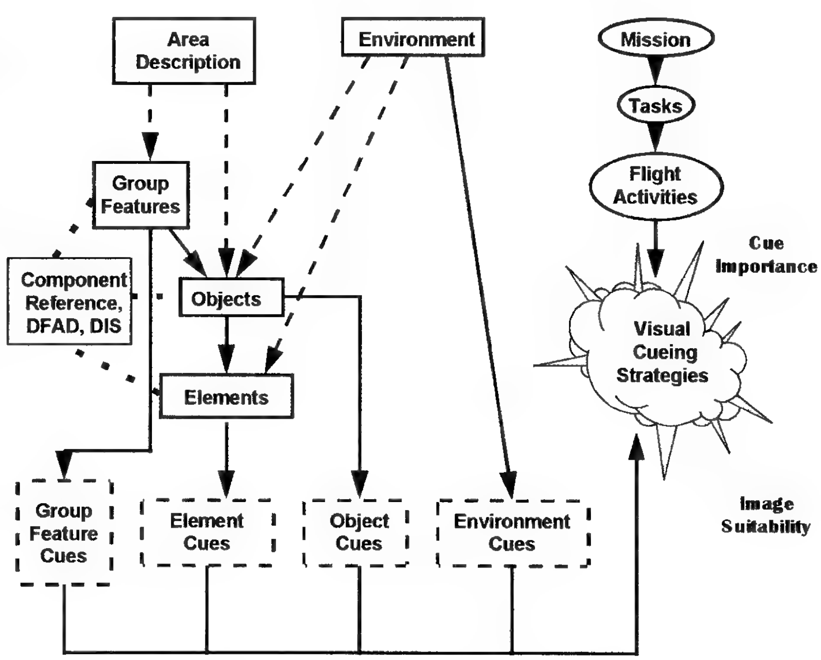

Figure 2. General Database Structure

Table 2. Highest Importance ratings for VCS's in a Battlefield attack mission

Visual Cueing strategy	Importance	Task	Activity
Coincidence of objects	9.32	Nap of the earth	Map position
Recognisable features	9.00	Nap of the earth	Map position
Vertical backdrop	9.00	Missile firing	Attitude
Streaming	8.96	Nap of the earth	Vertical flight path
Vertical backdrop	8.96	Low speed manoeuvring	Height agl
Ground rush	8.65	Nap of the earth	Ground Speed
Lateral backdrop	8.65	Low speed manoeuvring	Ground position
Lateral backdrop	8.65	Quick stop	Ground position
Line features	8.65	Missile firing	Heading
Line features	8.65	Nap of the earth	Track
Man-made object texture	8.65	Low speed manoeuvring	Ground position
Man-made object texture	8.65	Low speed manoeuvring	Height agl
Man-made object texture	8.65	Quick stop	Ground position
Natural texture	8.65	Low speed manoeuvring	Ground position
Natural texture	8.65	Low speed manoeuvring	Height agl
Natural texture	8.65	Quick stop	Ground position
Streaming	8.65	Nap of the earth	Track

the visual scene. It is these visual cueing strategies that link the requirements of the Service Operator who defines and knows the Operational Scenario to those of the Visual Scene Database Designer who defines and is knowledgeable about the Modelling Scenario.

4. CALCULATING PRIORITIES FOR MISSION AND SCENE COMPONENTS

On the mission side of the database numerical rankings can be given for the importance of visual cueing strategies to visual flight activities; for the importance of visual flight activities to tasks and for the precision needed for a task within a particular mission. An overall relative importance value to the mission can then be derived for a combination of visual cueing strategy, visual flight activity and task by multiplying the numerical values for each of the three combinations and taking the cubed root of the resulting number.

As an example of Visual Cueing strategy priorities, consider two missions

a. A full battlefield attack mission

b. A transit navigation mission that might be a mission for training emergency procedures

For the battlefield attack mission the preliminary dataset identifies 28 combinations with an importance level greater than 8 with the highest importance reaching 9.32. These 28 combinations include 9 of the 12 VCS's (counting both general and local recognisable objects as a single VCS during operations). The large number of conditions with importance greater than 8 illustrates the importance of visual scene information to the mission. The VCS's that are not present with an importance greater than 8 are Perspective, Surface Shading and Colour. Surface Shading and Colour were not rated very relevant to Visual Flight activities in Table 1 and this reduces their importance to any mission. Perspective was rated very relevant to Range

and Obstacle Avoidance Visual Flight activities, but is less important for these activities than the Recognisable Features VCS. The 17 conditions with the highest importance ratings are listed in Table 2

In contrast, if the training mission is restricted to transit navigation then there are no conditions with importance levels for VCS's that are above 8. The 18 conditions with levels of importance greater than 5 from the preliminary dataset are listed in Table 3.

Table 3. Highest Importance ratings for VCS's in a Transit Navigation mission

Visual Cueing Strategy	Importance	Flight Activity
Coincidence of objects	7.94	Map position
Recognisable features	7.66	Map position
Ground rush	7.11	Ground Speed
Line features	7.11	Track
Recognisable features	7.11	Range
Streaming	7.11	Track
Streaming	6.54	Ground Speed
Man-made object texture	6.21	Range
Natural texture	6.21	Range
Perspective	6.21	Range
Colour	5.85	Range
Recognisable features	5.85	Ground Speed
Streaming	5.85	Vertical flight path
Ground rush	5.65	Track
Vertical backdrop	5.65	Attitude
Colour	5.31	Map position
Man-made object texture	5.31	Map position
Natural texture	5.31	Map position

The lower levels of importance compared with the battlefield attack mission reflect the reduced importance of visual cues for this mission. Although these cues are clearly still necessary, a training mission may not be compromised if the quality of visual cues is reduced compared with those needed for a Battlefield attack mission.

The only 2 VCS's not represented in the conditions with importance levels greater than 5 are Surface shading and Lateral backdrop. Neither of these VCS's are particularly relevant to Visual Flight activities that are important to this mission.

It is interesting and an important point to note that Coincidence of objects and Recognisable features are the two most important VCS's for both missions and these occur for the Map position Flight activity. This reflects the importance to the success of the mission of recognising where the map location of the helicopter is throughout the mission. Pilots are very critical of visual scenes on simulators that do not satisfy these VCS's and this confirms their importance.

5. PRACTICAL APPLICATIONS OF THE STRUCTURED DATASET

Structured datasets of information relating visual scene details to mission task priorities can be used by both purchasers and suppliers of visual scene generation systems for specific flight training simulators. The purchaser can specify types of mission and their associated geographic or generic types of area that are to be practised on the simulator, and a level of image suitability that will be acceptable for the expected combination of flight and simulator training that will be used for the complete training activity. The types of visual scene components that will correspond to the specified missions and image suitability can be obtained from the dataset and the purchasers can modify any of these specification features until they are satisfied that they are suitable for the intended purpose.

The supplier can then use the specified mission types, area types and level of image suitability to obtain information on specific image detail, including standard library features, that are appropriate to meet the specification. This will provide a detailed specification that can be used to design and build a visual scene database and image display system that can be an acceptable form of compliance with the specification. If there is significant spare capability in an Image Generation system proposed by the manufacturer then

they may choose to enhance the level of image suitability or add optional mission types which will provide useful enhancements for the purchasers. (This is much more worthwhile than just improving 'realism' at random.) A manufacturer may also choose to offer a cheaper system that meets the basic specification with less spare capability.

The same structured dataset can also be used by the purchasers and supplier to define a mutually agreed acceptance test schedule for the complete image generation system.

6. CONCLUSIONS

The aim of the study was to specify the minimum scene content requirements of visual simulation systems to support the training of battlefield helicopter operations The human factors methods and procedures implemented during the study provided a successful way of collecting the information required to address this aim. In particular through semi-structured interviews, questionnaires and piloted simulation trials both the relative importance of visual cueing strategies to the battlefield helicopter attack mission and the effectiveness of many of the major visual scene components in supporting visual cueing strategies were established. It is recommended that these procedures should form the core of a battery of subjective, objective, physiological and behavioural techniques to be used in the development, testing and acceptance of rotary and fixed wing visual simulation systems for rotary and fixed wing operations.

A structured way of collecting and presenting the information gained from the study using a computer based relational database was outlined. It is concluded that the use of a relational data as a repository for the knowledge gained from this and subsequent studies is essential to providing answers to questions from customers, suppliers, scene modellers about visual scenes for particular training missions.

7. WHERE ARE THE CHALLENGES ?

The research reported in this paper has contributed significantly to ways of evaluating and specifying visual scenes for battlefield helicopter operations and has identified several additional challenges for the community.

- *Complete and document the design of the visual scene/mission database.* Appropriate actions should be taken to ensure that the design of the database is completed and functionally tested. This should include the design of standard forms for entering data, more complete definitions of the descriptions of the various terms used for Visual Cueing strategies, Visual Flight activities, etc. and for the description of visual scene components and also development of some standard queries to extract appropriate information from the dataset held in the database.
- *Generate a battlefield helicopter attack mission visual scene dataset using the completed dataset.* Put all relevant data for a Battlefield Attack mission into the completed database, including all the data from the present study. Verify all the mission based ratings with appropriate Service staff such as the helicopter instructors used in the present study.
- *Validation of scene content during training effectiveness studies.* The impact of the minimum scene content specification upon training effectiveness is a major challenge confronting the community and must be addressed.
- *Extend dataset to encompass other helicopter training missions.* Where appropriate personnel conducting visual simulation studies should be encouraged to implement the battery of techniques developed during the study alongside trials specific questionnaires. Additional piloted simulation studies for the few remaining visual cues and Visual Cueing strategies should be considered.
- *Usability assessment of the content and structure of the relational database.* A complete dataset preferably extended to cover a wide range of helicopter missions should be evaluated by MoD, a supplier and scene modeller to test its usability. This evaluation would be expected to identify some necessary changes to the standard queries and perhaps to the structure and types of data in the database.
- *Contribute to the development of international standards for visual scene description to improve capabilities for Distributed Interactive Simulation exercises.* The concept of this visual scene/mission database and the details in a complete dataset will provide unique inputs to assist in defining international standards in this field. The concept should be introduced into these discussions as soon as possible and this should be followed by demonstration of the completed dataset.
- *Provision of visual scene/mission datasets for other types of aircraft, e.g. fast jet low altitude missions.* Database design should be adapted to provide a dataset for other missions where visual scenes are important, e.g. fast jet low altitude missions. Existing data on visual scene effectiveness that are relevant to such missions should be put into the dataset and simulation trials conducted to evaluate any important visual scene components and Visual Cueing strategies where data is not available.

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VISUAL SYSTEM OPERATIONAL EVALUATION

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SUMMARY

This paper presents the results of an operational evaluation of the training effectiveness of three different visual technologies. Purpose of the program was to determine (1) trainability of low altitude tasks on available visual display technology; (2) demonstrate current visual simulation technology to users; (3) get feedback from those users to help define future visual requirements; and (4) provide information and data to support future simulation acquisition decisions. Three visual simulation display technologies at three different sites were evaluated: (1) a dome display with head tracked area-of-interest, (2) a rear-projection display, and (3) a fiber optic helmet mounted display. A team of highly experienced F-16C and F-15E instructor pilots evaluated each of the three display technologies. Three evaluation missions were flown by each pilot. At the completion of each evaluation mission, extensive questionnaires were completed and debriefings were conducted to rate the training capability of the visual system for each task. Results are presented for each of the three display systems evaluated. The results are expressed in terms of tasks that were rated trainable and those tasks that were not trainable in the system.

ABBREVIATIONS

AB	Air Base
ACC	Air Combat Command
AOI	Area-of-Interest
DART	Display for Advanced Research and Training
DB	Dive Bomb
DMPI	Desired Munitions Point of Impact
DTOS	Dive Toss
ESIG	Evans and Sutherland Image Generator
FOHMD	Fiber-Optic Helmet Mounted Display
FOV	Field of View
HAS	High Angle Strafe
HD	High Dive
HMD	Helmet Mounted Display
HUD	Heads-Up Display
LAB	Low Angle Bomb
LALD	Low Angle Low Drag
LAS	Low Angle Strafe
LATS	Low Altitude Training System
MTT	Multi-Task Trainer
NR	Not Rated
OFT	Operational Flight Trainer
RWR	Radar Warning Receiver
SAM	Surface-to-Air Missile
TSRA	Training System Requirements Analysis
USAFE	United States Air Force in Europe
VLD	Visual Level Delivery
WSO	Weapon System Officer

1. INTRODUCTION

Ground-based simulator training for tactical fighter aircrews is limited by lack of adequate visual display systems. Efforts to develop visual systems with the capability to provide useful tactics training have met with limited success. A major requirement of tactical visual systems is that the display must have an instantaneously large field-of -view (FOV) both horizontally and vertically. This requirement has been difficult for industry to meet and still provide resolution and brightness that is adequate to realistically train tactical flying tasks. Other constraints have been in the area of data base size and detail. Fighter aircraft rapidly traverse long ranges in a very short time span. This places major emphasis upon data base development and image generation. They also operate at altitudes ranging from the surface to thirty or forty thousand feet. The fighter pilot needs to be able to recognize objects such as another F-16 with sufficient detail to visually identify other aircraft at realistic tactical ranges, assess aspect angle of another aircraft, fly tactical formation, and identify ground vehicles, roads and bridges. This wide range of requirements has made it difficult for industry to develop a display system adequate to meet the full range of fighter training requirements.

In the past, the Air Force has undertaken operational evaluations to determine if new advances in visual system technology provide capability to train tactical flying tasks. Among these efforts were Project 2235, Air-to-Ground Visual Simulation Demonstration (1976), Simulator Systems Comparative Evaluations (1977, 1979), and F-15 Limited Field of View Visual System Training Effectiveness Evaluation (1984). The general findings of these efforts indicated that existing visual systems could train some but not all critical tactical flying tasks.

In March 1989, the United States Air Force In Europe (USAFE) requested assistance from Air Force Materiel Command to meet its low altitude training needs for the 1990s. USAFE aircrews were limited to train at altitudes no less than 250 feet and at airspeeds no more than 475-550 knots. However, pilots indicated that in time of war, threat conditions might require them to fly at altitudes as low as 100 feet. A training systems requirements analysis (TSRA) was conducted based upon the F-16C and F-15E weapon systems. Recommendations based upon the analysis indicated that modern visual systems have the potential to significantly enhance available tactical aircraft training and may assist in slowing down the loss of critical low altitude flying skills that are not frequently practiced due to range or safety constraints (1991). The consensus of most engineering and training

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experts involved in the analysis was that current image generation technology was adequate to support low altitude training but that image display technology needs further assessment. To verify adequacy of image display technology to support low altitude training, this operational evaluation, using highly experienced aircrews, was conducted.

2. SCOPE AND LIMITING FACTORS

The evaluation method used was an evaluation team composed of eight tactical fighter instructor pilots and two instructor Weapon Systems Operators (WSOs), with current F-16C, F-15E, and F-111 background, to evaluate three different image display technologies located at three different sites. The image display technologies evaluated were: (1) a two-channel head-tracked dome display located at Evans and Sutherland Corporation, Salt Lake City, UT; (2) a rear-projection mosaiced display, the Display for Advanced Research and Training (DART)* and a smaller display version (mini-DART)* located at Armstrong Laboratory, Williams Gateway Airport, AZ; and (3) a fiber-optic helmet mounted display (FOHMD) located at CAE Stolberg, Stolberg GE. An engineering assessment for each device configuration was conducted to verify the current visual systems display and image generator attributes.

* Similar display technologies

The focus of the evaluation was the training capability of various image display technologies in the high threat low-altitude environment. The evaluation was conducted over a seven month period beginning in January 1993 and ending in July 1993. This evaluation was conducted at commercial and government flight simulator facilities. Evaluations were performed based upon facility availability and were often separated in time by as much as two months. It was recognized that experimental order effects, i.e., order in which a display technology was evaluated, would be present but had to be accepted as part of the evaluation. The evaluation was an operational evaluation and was not structured as an experimental comparison. No transfer of training comparisons were made although evaluation aircrews were asked to rate the training capability of the visual display system under evaluation. Each system was evaluated to assess the tasks that were rated trainable.

Due to large differences in weapon system components and performance capability, it was not possible to compare one visual system to another. Nor was a comparison intended. Rather, the intent of this evaluation was to rate the capability of a given display technology to support training of a selected set of twenty-six tactical tasks.

The limited availability of operational instructor pilots and instructor WSOs and the limited availability of the flight simulation facilities meant that the evaluation at each site had to be structured to be conducted and completed within one week. The evaluation team was composed of a small, highly trained group of tactical fighter instructor pilots and instructor WSOs. Evaluators were given training on recognition of visual features related to displays, image generation, and data base. Evaluation WSOs were used to evaluate only the FOHMD technology at Site 3 and an F-4 FOHMD at Neuberg AB, GE since these sites were the only sites with a WSO visual system. Due to operational duty commitments, not all pilot evaluators participated in every visual system evaluation. The number of evaluators at any one site varied between five and seven instructor pilots.

Even though visual displays were the focus of the evaluation, and fidelity was not evaluated per se, it was recognized that cockpit differences, image generation and data base capabilities impacted training capability ratings.

Only subjective aircrew data was gathered during the operational evaluation. Objective data such as bombing scores, hits, etc., was not available at all sites. Engineering data was furnished by the site organization and verified by evaluation team engineering personnel. The evaluation did not assess specific hardware. Therefore operational suitability issues were not evaluated although general availability of systems was noted.

3. METHOD OF ACCOMPLISHMENT

The evaluation team was composed of a pool of eight fighter pilots and three weapon system operators (WSOs) specifically selected for their fighter experience and training background. All pilots and WSOs had extensive fighter experience in such weapon systems such as F-4, A-10, F-15C, F-15E, and F-16. Two of the pilots had combat experience in the Middle East Conflict and two pilots were Fighter Weapons School graduates. During the evaluation period, one evaluation pilot was selected for the Thunderbird Demonstration Team. Average flying time for pilots was 1989 hours. Average instructor pilot time was 1039 hours. Average flying time for WSOs was 2213 hours. Average instructor time for WSOs was 983 hours.

Training for the team was provided in visual system technology and the evaluation process. Classroom instruction and demonstration training on visual system technology were given to evaluation pilots and WSOs for recognition of visual features related to visual displays, visual image generation, and data base. This training enabled the evaluators to assess the interrelationships of visual system components and to focus on the image displays for training capability ratings.

The same general evaluation methodology was used at each site with minor differences as required by the system configuration and data base availability.

The evaluation was conducted at each site for a one week period. Four generic tactical missions were constructed to permit each pilot to evaluate twenty-six selected tactical flying tasks. See Table 1. Not all tasks were flown on each mission but the missions were developed to permit each of the tasks to be evaluated at least once during the evaluation missions if the site equipment and data base permitted. Each mission required approximately 1 hour to complete. The first mission was a familiarization mission. The next three missions were evaluation missions designed to evaluate air-to-surface tasks such as, tactical formation, low altitude evasive maneuvering,

and low altitude air-to-surface weapon employment. The pilot tasks for the missions were based upon results from the USAFE Low-Altitude Training System (LATS) Requirements Analysis (1991) and modified by Air Combat Command

#	Pilot Tasks
1	Tanker rendezvous
2	Tactical formation from fingertip
3	Tactical formation above 500 feet
4	Combat descent
5	Tactical formation below 500 feet
6	Single ship low level
7	Visual low level navigate to initial point
8	Mutual support/lookout in various tactical formations
9	Detect visual threats
10	Detect electronic threats
11	Terrain Masking (direct/indirect)
12	Individual/formation threat reactions
13	Tactical instruments cross check
14	Visual target acquisition/identification
15	Coordinated tactical attack
16	Low altitude weapon delivery (LAS, LALD, LAB,VLD)
17	High altitude weapon delivery (HAS, HD, DB, DTOS)
18	Reform after tactical attack
19	Target reattack
20	Aircraft battle damage check
21	Low altitude intercept
22	AIM-9 employment
23	Low altitude air-to-air gun employment
24	Flight lead responsibilities
25	Wingman responsibilities
26	Situational awareness of tactical situations

Table 1 List of Pilot Evaluation Tasks

For Site 3 only, four missions were developed to permit each WSO to evaluate twenty-two selected tactical tasks. These missions were the same length as the missions for evaluation pilots and were integrated into the missions for the pilot evaluators. The first mission was a familiarization mission; the next three missions were evaluation missions. The WSO tasks were identified as high value tactical flying tasks by Air Combat Command (ACC) and were correlated to tasks that would be performed by the pilots during missions at Site 3.

Approximately two days prior to arrival of the evaluation team, the lead evaluation pilot and WSO would visit each site to prepare for the evaluation. They would develop and fly the four generic missions to make adjustments in the flight profiles for the missions based upon limitations of the hardware and database capabilities of each site.

Upon arrival of the team, evaluators were given a briefing on the system at the site, the missions to be flown, evaluation procedures, and general plans for the week. Prior to each mission, evaluators were briefed on the specific mission to be flown.

Pilot and WSO evaluators flew each mission and then rated the tasks flown for training capability using a five point rating scale. With the exception of the familiarization mission, all evaluators completed an extensive questionnaire after each mission. This questionnaire was used as the basis for an evaluator debrief to explain ratings. The ratings and questionnaire data were later entered into computer data files that were used as an aid to data analysis. The debriefings were tape recorded and used as additional references to interpret the data.

The engineering data collection was conducted as follows. Prior to going to the evaluation site, the engineering specialist requested specific engineering data from the site representatives. Two days prior to the team arrival, the engineering specialist visited the site and began collecting and verifying the data provided. The specialist remained on site throughout the evaluation and was responsible to track down limitations of the system and problems noted by the evaluation pilots and WSOs during their missions.

The percentage of acceptable or better ratings for each task was compared to the criteria to arrive at assessments. The measures of effectiveness were the evaluation pilot or WSOs subjective ratings and the evaluation team's assessment of the capability of each system to train pilots or WSOs in an operational training environment. The criteria were that at least 80 percent of the evaluators must rate each task a 3 or better (first criterion) or the sub-objective must receive an overall acceptable assessment by the evaluation team (second criterion).

The intent of the engineering evaluation was to document visual system performance as it existed at the time of the operational evaluation, not to assess the performance of each visual system. Using the pilot's assessment of the visual system's capabilities to train the identified tasks, and the engineering evaluation documented performance, systems engineers will be better able to translate the user's task requirements into a visual system performance specification.

4. RESULTS

Site 1: Two-Channel Head-Slaved Area of Interest (AOI) Dome/ ESIG 3000.

Evaluation Cockpit
The evaluation cockpit was a generic aircraft cockpit mounted on a pedestal within a 24 foot diameter dome. The cockpit had instruments to represent standard aircraft flight parameters such as attitude, altitude, airspeed, vertical velocity and, engine instruments. It had a control stick and throttle controls that were representative of a generic fighter, and permitted control of flaps, speed brakes, and weapons release. Landing gear control was located on the panel. The cockpit had some weapons radar and fire control capability but not a fully capable integrated system found in current fighter aircraft.

There was no Head-Up Display (HUD) and tactical instrument cross-check was all accomplished inside the cockpit. Sound and motion were not simulated. Flight performance of the simulated aircraft was representative of a generic high performance jet fighter aircraft (although not necessarily an F-16 or F-15E.

Image Display
The two-channel image display provided one channel for a head tracked background image with the other channel inserted, centered as an area of interest (AOI) scene. The AOI was superimposed on the background scene directly in front of the pilot's head. Both scenes were projected on the 24 foot dome by light valve projectors mounted above and behind the cockpit.

Image Generator
The image generator was a two channel ESIG 3000 built by Evans and Sutherland Corporation.

Data Base
The data base was representative of the Hunter-Liggett range in the USA (not correlated to real world).

Discussion
From the list of twenty-six tasks that were initially identified, eighteen tasks were able to be evaluated during the missions flown.

Tanker rendezvous was eliminated by team consensus since this task was not supportable by the simulation capability, is normally performed frequently during normal operational training missions, and would have required unacceptable additional mission time to accomplish. Seven tasks were not able to be performed due to simulator system limitations and were not evaluated. It was believed that all of are correctable with improvements to the simulation system. However, the tasks would still need to be evaluated for training capability.

Of the remaining eighteen tasks, the Two-Channel Dome AOI visual system was evaluated as being capable of supporting operational training for four tasks. These four tasks received a rating of 3 or greater for at least 80% of the task ratings by the evaluation pilots. The four tasks that met the criterion were: Task #11, terrain masking (89%); Task #14, visual target acquisition/identification (80%); Task #17, high altitude weapon delivery (HAS, HD, DB, DTOS) (93%); and Task #19, target reattack (95%). Pilot comments indicated areas of improvements for these tasks even though they were rated acceptable (three or greater). Most frequently cited areas of improvement were: (1) wider AOI inset area and background scene and (2) improved resolution in background scene outside the AOI. The number of tasks rated trainable and not trainable are shown in Table 2.

Two Channel Head Tracked Area of Interest Dome	
Tanker rendezvous	NR
Tactical formation from fingertip	⊗
Tactical formation above 500 feet	⊗
Combat descent	⊗
Tactical formation below 500 feet	⊗
Single ship low level	⊗
Visual low level navigate to initial point	⊗
Mutual support/lookout in various tactical formations	⊗
Detect visual threats	⊗
Detect electronic threats	NR
Terrain Masking (direct/indirect)	●
Individual/formation threat reactions	⊗
Tactical instruments cross check	⊗
Visual target acquisition/identification	●
Coordinated tactical attack	NR
Low altitude weapon delivery (LAS, LALD, LAB,VLD)	⊗
High altitude weapon delivery (HAS, HD, DB, DTOS)	●
Reform after tactical attack	NR
Target reattack	●
Aircraft battle damage check	NR
Low altitude intercept	⊗
AIM-9 employment	NR
Low altitude air-to-air gun employment	NR
Flight lead responsibilities	NR
Wingman responsibilities	⊗
Situational awareness of tactical situations	⊗

⊗ - Did Not Meet Criteria
● - Met Criteria

NR - Not Rated

Table 2 Tasks Rated Trainable and Not Trainable

Fourteen tasks did not meet the criterion for various reasons. Tactical formation from fingertip, tactical formation above 500 feet, and tactical formation below 500 feet did not meet the criterion for the following reasons: Unrealistic head motion was required to place the high resolution AOI onto the wingman to check his position. Pilots indicated that this is not a normal flying habit. Rather they indicated fighter pilots normally move their eyes to pick up the target rather than make large head movements. Another frequently mentioned problem in performing these tasks was the target aircraft suddenly changed color to a bright green as distance increased to approximately 1200 feet to 1500 feet.

Combat descent did not meet the criterion due to difficulty in determining altitude visually. Several pilots indicated the ground appeared to be out of focus, however, buildings appeared to be in focus. Several indicated that other than the horizon, there were no adequate indications they were approaching the ground. Normal ground rush was not provided in the visual simulation. Small objects appeared to be blurry at longer ranges. Pilots also indicated accentuated head movements "to steer the AOI" were also required to perform this task. Again, the large head movements were not

considered natural and impacted normal tactical cross-check pacing.

Single ship low level did not meet the criterion due to exaggerated head movement to move the AOI to the desired visual area, lack of adequate detail to maintain low altitude without reference to instruments, limited field of view and low resolution in the periphery, and lack of sufficient detail in data base (particularly forested areas).

Visual low level navigate to initial point did not meet the criterion. Frequently cited problems in performing this task were the exaggerated head movements required to move the high resolution AOI inset and lack of resolution in the peripheral (background) scene.

Mutual support/lookout in various tactical formations did not meet the criterion due to the exaggerated head movement to steer the AOI and the target projector providing an aircraft image that was too easy to see.

Detect visual threats did not meet the criterion because; (1) the aircraft threats were too easy to see due to their bright green color, (2) the surface to air missile (SAM) threats were not realistic due to visual display system resolution, lack of smoke and fire trails, and (3) unrealistic head movements were required to detect threats.

Individual/formation threat reactions did not meet the criterion due to a combination of factors. Unrealistic head movements were required to detect visual threats. Since there was no Radar Warning Receiver (RWR) indicator in the cockpit, this additional piece of information was missing to assist the pilots to determine threat location and type.

Tactical instruments cross check did not meet the criterion due to lack of adequate instrumentation to perform the cross-check. The cockpit did not have a HUD, RWR indicator, or radar display. Without these systems, the task could not be realistically performed.

Low altitude weapon delivery (LAS, LALD, LAB, VLD) did not meet the criterion because of the head movement required to steer the high resolution AOI and the pilots indicated there was a noticeable lag in the visual system. The limited high resolution AOI forced unnatural scan patterns. The majority of the pilots reported the resolution was adequate for target identification and desired munitions point of impact (DMPI) selection. However, most pilots indicated the lack of peripheral cues and the limits in the high resolution AOI made scanning unnatural and detracted from weapons delivery. They reported having a less than full peripheral visual display made aircraft attitude and pop up attacks more difficult to evaluate.

Low altitude intercept did not meet the criterion primarily because the visual phase of a low altitude intercept requires radar work, switchology, geometry analysis, and threat analysis using both visual and avionics systems.

Wingman responsibilities did not meet the criterion due to the exaggerated head movements required to place the AOI on desired visual areas and the popping in of the high contrast green aircraft between 1200 and 1500 feet.

Situational awareness of tactical situations did not meet the criterion primarily due to the lack of other than visual cues.

Additional FOV and Resolution
Evaluation pilots indicated that they believed a wider field of view for both the inset AOI and the background scene was required. Most pilots reported that seeing the black edges of the background scene was very distracting.

Target Projector
The pilots indicated the target projector produced a green image that was too bright. Pilots indicated that at longer ranges, the contrast of a real world aircraft is not as good as the current simulated aircraft.

Generic Fighter Cockpit
Evaluation pilots indicated the lack of a fighter cockpit and HUD adversely impacted the results of this study. The generic fighter cockpit at Site 1 did not permit the normal instrument cross check. It did not have a weapons system radar or RWR. Most importantly, it was missing a HUD.

Image Generator and Data Base
(Size and optimization for Air to Surface) The pilots reported the data base needed to have more cultural and geographic detail available. The pilots pointed out that at low altitude they can see numerous features such as people, vegetation, trees, vehicles, animals, etc.; and all of these objects give them a sense of altitude.

Head-tracking
Head-tracking forced the pilots to use exaggerated head movements to visually acquire a target or visual object. Head-tracking required the pilots to steer the AOI to the area they wanted to see. This resulted not only in changes to normal visual habit patterns but also caused them to fixate on the visual object longer than normal.

Site 2: Display for Advanced Research and Training (DART)/Compu-Scene IVA

Evaluation Cockpit
The evaluation cockpit was an F-15C Mission Tactics Trainer (MTT) developed by Armstrong Laboratory. The cockpit replicated the physical and functional controls and displays of the F-15C weapon system. The cockpit provided an integrated weapons radar and fire control system and had a projected HUD. Flight performance of the simulated aircraft was representative of the F-15C weapon system. The cockpit was situated inside the display.

Image Display
The image display was a nine-channel mosaiced rear-projection flat screen wrap-around display that provided a total FOV of 360 degrees horizontal by 110 degrees vertical.

Image Generation
A General Electric Compu-Scene IVA furnished the image generation for the evaluation,

Data Base
The data bases used in the evaluation were representative of a portion of the state of Washington and Germany.

Site 2: Mini-Display for Advanced Research and Training (Mini-DART)/Compu-Scene IVA

Evaluation Cockpit
The evaluation cockpit was an F-15C Mission Tactics Trainer (MTT) developed by Armstrong Laboratory. See the description for the DART.

Image Display
The image display was an eight-channel mosaiced rear-projection flat screen wrap-around display that provided a total FOV of 360 degrees horizontal by 110 degrees vertical. This display had a smaller footprint than the DART. Also, the rear quadrant display was a single flat screen that was lowered into place after the pilot had entered the cockpit.

Image Generation
Same as the DART.

Data Base
Same as the DART.

Discussion
Twenty four tasks were evaluated in missions on the DART and Mini-DART.

Tanker rendezvous was not evaluated at Site 2 because the evaluation team believed that this task was not supportable by the simulation capability and is normally performed frequently during normal operational training missions and does not need to be taught in the simulator. Aircraft battle damage check was not performed because of the unavailability of an aircraft model to fly the task upon. This task requires close maneuvering in relation to another aircraft.

Of the twenty-four remaining tasks, the DART visual system was evaluated as being capable of supporting operational training for ten tasks. These ten tasks received a rating of 3 or greater for at least 80% of the task ratings by the evaluation pilots.

Although the tasks shown were rated acceptable for training capability, pilots comments indicated areas of improvements. Most frequently cited areas were: (1) objects abruptly appeared on the display; (2) pilots had to rely more upon the radar altimeter and HUD to obtain altitude information; (3) due to inadequate resolution of the display, blemishes on the display screen were often mistaken for air-to-air threats; and (4) the on/off switching of the visual display channels located at the 6 O'clock position of the display needs to be improved so that it is less noticeable and distracting. Table 2 presents the tasks rated trainable and not trainable.

Display for Advanced Research and Training (DART)	
Tanker rendezvous	NR
Tactical formation from fingertip	⊗
Tactical formation above 500 feet	⊗
Combat descent	●
Tactical formation below 500 feet	⊗
Single ship low level	●
Visual low level navigate to initial point	●
Mutual support/lookout in various tactical formations	⊗
Detect visual threats	⊗
Detect electronic threats	●
Terrain Masking (direct/indirect)	⊗
Individual/formation threat reactions	⊗
Tactical instruments cross check	●
Visual target acquisition/identification	⊗
Coordinated tactical attack	⊗
Low altitude weapon delivery (LAS, LALD, LAB,VLD)	●
High altitude weapon delivery (HAS, HD, DB, DTOS)	⊗
Reform after tactical attack	⊗
Target reattack	●
Aircraft battle damage check	NR
Low altitude intercept	⊗
AIM-9 employment	●
Low altitude air-to-air gun employment	●
Flight lead responsibilities	⊗
Wingman responsibilities	⊗
Situational awareness of tactical situations	●

⊗ - Did Not Meet Criteria
● - Met Criteria
NR - Not Rated

Table 2. Tasks Rated Trainable and Not Trainable on the DART.

Tactical formation from fingertip, tactical formation above 500 feet, and tactical formation below 500 feet did not meet the criterion for the following reasons: Pilots reported that they could not get close enough to fly reasonable fingertip formation. The majority of the pilots reported there was not enough detail to fly fingertip formation. Several pilots reported the 10 O'clock and 2 O'clock display screens appeared a little blurry compared to the front display screen and this contributed to the difficulty in accomplishing the task.

Mutual support/lookout in various tactical formations and detect visual threats did not meet the criterion. Pilots reported the resolution outside 3000 to 5000 feet was not adequate to

perform the task without using more radio calls and other sensor information not normally required in actual flight conditions.

Terrain masking (direct/indirect) did not meet the criterion because pilots said there was insufficient scene detail to provide them with altitude cues.

Individual/formation threat reactions did not meet the criterion. There was a lack of sufficient resolution outside the 3000 to 5000 foot range.

Visual target acquisition/identification did not meet the criterion. The lack of resolution outside 4000 feet made target identification occur too late. Pilots said target identification was satisfactory inside of this range.

Coordinated tactical attack did not meet the criterion due to of the lack of resolution. Pilots said if one of the aircraft responded to a threat, then returning to tactical formation became a major problem due to the difficulty of reacquiring wingman to compensate for a lack visual cues.

High altitude weapon delivery (HAS, HD, DB, DTOS) did not meet the criterion. Targets appeared in the scene too late and lacked sufficient detail.

Reform after tactical attack did not meet the criterion because of the lack of adequate resolution outside the 3000 to 5000 foot range. Pilots said the visual cues were too poor for good tactical formation rejoins. They reported that because of the lack of visual resolution, they had to talk to their wingman to get within visual range (3000 to 5000 feet). Pilots indicated the visual display was not adequate to get back together outside this range.

Low altitude intercept did not meet the criterion. The target aircraft did not show up at the expected distances with the proper clarity.

Flight lead responsibilities and wingman responsibilities did not meet the criterion. Low resolution of the display forced the pilots to rely abnormally upon instrument cross checks to analyze closure and range due to degraded visual cues. Pilots reported lack of resolution and detail of the lead aircraft or wingman aircraft would not to permit realistic tactical formation work.

Results for the Mini-DART at Site 2 indicated the visual system was evaluated as being capable of supporting training for eight of the twenty-four tasks (see Table 3-7). These eight tasks received a rating of 3 or better for at least 80% of the task ratings by the evaluation pilots. For the most part, the results on the Mini-DART parallel those of the DART since they are relatively similar technology. The Mini-DART is slightly smaller and the rear display arrangement differs from the DART in that a single display panel is used rather than several display panels. There were some differences between the trainable tasks on the DART and the tasks rated trainable on the Mini-DART.

The differences in the tasks rated trainable and not trainable are as follows. Task #6, Single ship low level was not rated as trainable on the Mini-DART where it had been rated as trainable on the DART. Task #16, Low altitude weapon delivery (LAS, LALD, LAB, VLD) was rated not trainable on the Mini-DART where it had been rated as trainable on the DART. Pilot comments indicated that the close proximity of the display screens in the Mini-DART may have been the cause of lower ratings. Task #21, Low altitude intercept was rated trainable on the Mini-DART but not trainable on the DART (71%) (Since the percentages do not differ by much (80% vs 71%) this change may be a statistical anomaly resulting from slight rating shifts).

Resolution
Pilots indicated the resolution of the DART and Mini-DART was not adequate at ranges outside 3000 to 5000 feet. Lack of adequate resolution impacted their ratings on tasks involving formation flight, threat identification, and target acquisition .

Brightness
Pilots commented that the brightness for both the DART and Mini-DART was very good.

Image Generator and Data Base
Several of the pilot comments and their ratings reflected limitations of the Compu-Scene IVA image generator and the data base. At the time of the evaluation, Site 2 was performing an air-to-air evaluation and both the image generator and the data base had been optimized for air-to-air operations. The lack of detail in some of the ground targets may have been due to optimization of the data base for air-to-air operations

Head-tracking
The majority of evaluation pilots reported that the head-tracking for the DART and Mini-DART was adequate. However, several pilots commented the on/off switching of the display scene for the aft display panel was noticeable and distracting.

Site 3: Fiber Optic Helmet Mounted Display/ESIG-1000.

Evaluation Cockpit
The evaluation cockpit was an Operational Flight Trainer (OFT) for the German Tornado Weapon System. It accurately replicated the physical and functional controls, flight systems, and flight characteristics of the Tornado aircraft. The cockpit provided an integrated weapons radar and fire control system and had a HUD. Fully integrated motion simulation was provided by (1) a six-post 60 inch stroke platform motion base, (2) a g-seat, and (3) a g-suit.

Image Display
The 3-channel fiber optic helmet mounted display (FOHMD) was fitted onto the pilot's and WSO's head after they had entered the cockpit.

Image Generation
An Evans and Sutherland ESIG-1000 provided the image generation for the evaluation.

Data Base
The data base used in the evaluation was an accurate representation of south central Germany.

Discussion - Pilots
Evaluation pilots flew twenty-four tasks from the list of twenty-six tasks that were initially identified.

Tanker rendezvous was eliminated by team consensus since this task was not supportable by the simulation capability and is normally performed during normal operational fighter training missions. Detect electronic threats was not evaluated in order to avoid security classification issues with the Tornado radar and RWR system.

Of the remaining twenty-four tasks, the FOHMD visual system was evaluated as being capable of supporting operational training for nine tasks. These nine tasks received a rating of 3 or greater for all task ratings by the evaluation pilots. Pilots who evaluated the system commented very favorably on the brightness of the display. Several areas of improvements were identified for the above tasks; (1) the ability to make head movement left or right and up to check high 12 o'clock is too restricted by the fiber optic cables; (2) instrument cross-checking in the cockpit was too time consuming due to the low visibility of instruments within the cockpit; transitioning from outside to inside the cockpit was very difficult particularly if the display information was on the attack radar display; (3) blemishes in the image display caused by broken fiber optic bundles were distracting since pilots had to differentiate whether it was a threat aircraft or a blemish; and (4) the eye tracked area of interest needed to be larger. Table 3 presents the tasks that were rated trainable and not trainable.

Fiber Optic Helmet Mounted Display (FOHMD)	
Tanker rendezvous	NR
Tactical formation from fingertip	⊗
Tactical formation above 500 feet	⊗
Combat descent	●
Tactical formation below 500 feet	⊗
Single ship low level	●
Visual low level navigate to initial point	●
Mutual support/lookout in various tactical formations	⊗
Detect visual threats	⊗
Detect electronic threats	NR
Terrain Masking (direct/indirect)	⊗
Individual/formation threat reactions	⊗
Tactical instruments cross check	⊗
Visual target acquisition/identification	⊗
Coordinated tactical attack	⊗
Low altitude weapon delivery (LAS, LALD, LAB,VLD)	●
High altitude weapon delivery (HAS, HD, DB, DTOS)	●
Reform after tactical attack	⊗
Target reattack	●
Aircraft battle damage check	●
Low altitude intercept	⊗
AIM-9 employment	●
Low altitude air-to-air gun employment	●
Flight lead responsibilities	⊗
Wingman responsibilities	⊗
Situational awareness of tactical situations	⊗

⊗ - Did Not Meet Criteria
● - Met Criteria

NR - Not Rated

Table 3. Tasks Rated Trainable and Not Trainable for the FOHMD.

Fifteen tasks did not meet the criterion for various reasons.

Tactical formation from fingertip, tactical formation above 500 feet, and tactical formation below 500 feet did not meet the criterion for the following reasons: Pilots indicated the area of interest (AOI) was too small and the background imagery on the display lacked enough resolution to keep track of wing men while avoiding the ground and attempting to perform an instrument cross check.

Mutual support/lookout in various tactical formations did not meet the criterion for the following reasons: Pilots said the bulkiness and difficulty of moving the helmet due to restrictions imposed by the fiber optic cables made it too difficult to check the 6 o'clock or high 12 o'clock position. Broken fiber optic bundles also degraded the display. The pilots also reported that several times during their missions, the opposite eye from the direction that they were looking would black out when they moved their eyes to the extreme left, right, or up: this was extremely distracting and forced them to change their normal visual scan technique.

Detect visual threats, individual/formation threat reactions, and visual target acquisition/identification did not meet the criterion for the following reasons: Pilot comments indicated it was almost impossible to see a threat if it was not in the high resolution AOI. Visual pick-up of the threat at long ranges was too difficult.

Terrain masking (direct/indirect) did not meet the criterion for the following reasons: Pilot interviews indicated the texturing of the ground needed improvement to provide better low altitude cues (this problem is a limitation of the image generator but manifests itself in this task).

Tactical instruments cross check did not meet the criterion for the following reasons: Pilots indicated they could not easily look through the helmet mounted display optics into the cockpit and quickly gather the needed information.

Coordinated tactical attack and reform after tactical attack did not meet the criterion for the following reasons: Pilots reported that their visual search patterns were significantly changed; they had to look directly at their wingman in order to see them whereas in actual flight they would use their peripheral vision more.

Low altitude intercept did not meet the criterion: Pilots reported pure visual intercepts were generally not possible due to short range visual pick-up.

Flight lead responsibilities did not meet the criterion for the following reasons. Pilots indicated that their visual search patterns were changed due to the lack of resolution in the background image of the FOHMD. To confirm the wing man's position, pilots reported they had to stare at them with the AOI longer than normal.

Wingman responsibilities did not meet the criterion for the following reasons: Pilots stated lack of detail of the flight lead at ranges greater than 10,000 feet adversely affected their rating.

Situational awareness of tactical situations did not meet the criterion for the following reasons: The majority of evaluation pilots reported that they were unable to maintain situation awareness adequately using the FOHMD due to difficulty in moving the headgear to check 6 o'clock and the broken fiber optic bundles that forced them to take more time to differentiate between threat aircraft and blemishes.

Discussions - WSOs

Twenty-two tasks were identified for possible evaluation by the WSO evaluators. Of these tasks, twenty-one tasks were able to be evaluated during the WSO missions using the FOHMD.

Detect electronic threats was not evaluated. Lack of time to train WSOs to proficiency in these systems and desire to avoid security classification issues precluded meaningful evaluation of the task.

Of the remaining twenty-one tasks, the FOHMD visual system was evaluated as being capable of supporting operational WSO training for eleven tasks. These eleven tasks received a rating of 3 or greater for all ratings of the task by the WSOs. See Table 4.

FOHMD - WSO Tasks	
Single ship low level	●
Visual low level navigate to initial point	●
Mutual support/lookout in various tactical	⊗
Intraflight coordination/communication	●
Intercockpit coordination/communication	●
Detect visual threats	⊗
Detect electronic threats	NR
Tactical instruments cross check	⊗
Visual target acquisition/identification	⊗
Coordinated tactical attack	●
Low altitude weapon delivery (Radar/EO)	●
High altitude weapon delivery (Radar/EO)	●
Reform after tactical attack	⊗
Target reattack	●
Aircraft battle damage check	●
Low altitude intercept	⊗
Situational awareness of tactical situations	⊗
Direct tactical formation	⊗
Direct individual/formation threat reactions	⊗
Direct target attack/reattack	●
Direct reform	⊗
Direct egress	●

⊗ - Did Not Meet Criteria
● - Met Criteria

NR - Not Rated

Table 4. Tasks Rated Trainable and Not Trainable for the FOHMD by WSOs.

Ten tasks did not meet the criterion for various reasons.

Mutual support/lookout in various tactical formations did not meet the criterion for the following reasons: The WSOs indicated that they were unable to perform this task adequately since they were unable to check their six o'clock position for threats. The difficulty of moving the FOHMD due to the routing of the fiber optic cables was the primary problem.

Detect visual threats did not meet the criterion for the following reasons: WSOs indicated that ratings of this task were impacted by the difficulty of moving the FOHMD due to the routing of the fiber optic cables. They indicated that their normal scan patterns were impacted; they could not check high 6 o'clock due to the visual system limits.

Tactical instruments cross check did not meet the criterion for the following reasons: This task was difficult to perform due to the difficulty of looking through the FOHMD into the cockpit. Even with back lighting, the instruments were difficult to see and quickly get information.

Visual target acquisition/identification did not meet the criterion for the following reason: The visual target could not be acquired and identified at normal ranges. WSOs had to wait until the visual target was closer than usual and this was not acceptable.

Reform after tactical attack did not meet the criterion for the following reasons: WSOs stated that they were unable to see wingman at normal reform ranges.

Low altitude intercept did not meet the criterion for the following reasons: WSOs indicated that there was not enough detail and contrast for threat aircraft to give early acquisition and identification. This made the task of intercept difficult to perform.

Situational awareness of tactical situations did not meet the criterion for the following reasons: WSOs stated that they rated this task low because they were unable to spot bandits (threat aircraft) at normal ranges.

Direct tactical formation did not meet the criterion for the following reasons: WSOs indicated that they had to work too hard to keep visual contact with flight leads or wingman. Much of this they said was due to the low contrast of the visual image of other formation aircraft in the high resolution AOI.

Direct individual/formation threat reactions did not meet the criterion for the following reasons: Both WSOs indicated that they were unable to scan an area visually as rapidly as they normally do in actual flight. This was due to the low contrast of aircraft against the sky. This made it much more difficult to detect and then identify an aircraft.

Direct reform did not meet the criterion for the following reason: Both WSOs indicated that the low visual contrast of the lead aircraft against the sky made it too difficult to determine which way lead was heading.

Resolution
Pilots and WSOs indicated that the resolution of the AOI was very good but that the resolution in the area outside the AOI needed improvement.

Brightness
Pilots commented very favorably upon the brightness of the display. However, display brightness was degraded as fiber optic bundles were broken during the evaluation.

Tornado Fighter Cockpit
(Transition to a wing-sweep aircraft) Pilots and WSOs did not have any problem transitioning to flying the Tornado fighter simulator. Although none of the pilots had flown an aircraft with adjustable wing sweep, the transition to the Tornado was accomplished with minimum difficulty.

Image Generator and Data Base
The Pilots and WSOs liked the Germany data base. The majority of the evaluation aircrews had flown over similar areas of Germany during deployments or while stationed in Europe.

Head-tracking and Eye Tracking
The majority of the evaluation missions were flown using eye-tracked AOI. Pilots liked this feature when it was used. They commented that the AOI needs to be made larger and there needs to be better resolution in the background channel of the visual display.

Eye Tracking and Calibration Process
The procedures needed to provide eye tracking required that each pilot and WSO evaluator have a special custom fitted helmet liner. It also required a special eye tracking alignment process be conducted in the cockpit after the pilot or WSO had strapped in.

Head Movement Limitations
A major negative criticism of the display concerned the restrictions to normal head movement with the FOHMD. The routing of the fiber optic bundles restricted head movement and required extra effort on the part of the user when looking aft of the three-nine line. Due to their size and location, pilots reported difficulty in checking 6 o'clock and at the high 12 o'clock position. A subsequest visit to Neuberg AB, GE indicated that these restrictions has been removed through re-routing the fiber optic cables.

Fiber Optic Bundle Wear
Over the period of the evaluation, movement of the fiber optic cables resulted in breakage of the individual fiber optic bundles. The result was a darkening of the displayed image.

Motion Simulation
The integrated motion systems at Site 3 were representative of the latest state of the art in motion systems. Pilots and WSOs commented that the combination of the six-degree of freedom platform motion system, g-seat, and g-suit provided very realistic motion cueing. The consensus was that the motion simulation was outstanding; however its impact to training is unknown.

5. CONCLUSIONS

Throughout the visual evaluations, the importance of area of coverage, scene content, and scene detail of the visual presentations for operational training continued to surface. The evaluation team believes that realistic low altitude operational fighter training requires large visual data bases, with realistic threat modeling, high scene content, and high scene detail.

To accommodate realistic threat modeling, scene content, and accurate data bases requires a high end image generator. Image generators presenting data bases for tactical training must be able to rapidly process large quantities of data in a timely manner so that the aircrew member can realistically see it.

The team believes that evaluations of this type should be accomplished using senior instructor pilots or WSOs. Highly experienced instructor pilots and instructor WSOs are experienced in teaching flying principles to new students as well as experienced aircrew members returning to flying. They know what it takes to train the full range of students and can comprehensively express training issues to other disciplines so that they are understood.

Overall, the evaluation team believed that texturing in the displayed image can provide helpful cues for low altitude flight. However, a single level of texturing does not provide adequate cues required by pilots for low altitude flight using visual information. Texturing should become sharper in focus as the range from the textured object decreases. Multiple levels of texturing are a possible solution and should be evaluated.

Based upon the three evaluations, the evaluation team believes that single ship air-to-ground tasks are trainable now with the right combination of database, image generator, and matched visual display system.

The evaluation team does not believe that current systems provide adequate resolution, contrast, and brightness to allow for dynamic air model discrimination. Dynamic air models refer to anything (another aircraft, SAM, air-to-air missile, flack, bullets, etc.) in the airspace that the pilot or WSO must assess it's attitude, range, etc.

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Yaw Motion Cues in Helicopter Simulation

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1. SUMMARY

A piloted simulation that examined the effects of yaw motion cues on pilot-vehicle performance, pilot workload, and pilot motion perception was conducted on the NASA Ames Vertical Motion Simulator. The vehicle model that was used represented an AH-64 helicopter. Three tasks were performed in which only combinations of vehicle yaw and vertical displacement were allowed. The commands issued to the motion platform were modified to present the following four motion configurations for a pilot located forward of the center of rotation: 1) only the linear translations, 2) only the angular rotation, 3) both the linear translations and the angular rotation, and 4) no motion. The objective data indicated that pilot-vehicle performance was reduced and the necessary control activity increased when linear motion was removed; however, the lack of angular rotation did not result in a measured degradation for almost all cases. Also, pilots provided subjective assessments of their compensation required, the motion fidelity, and their judgment of whether or not linear or rotational cockpit motion was present. Ratings of compensation and fidelity were affected only by linear acceleration, and the rotational motion had no significant impact. Also, when only linear motion was present, pilots typically reported the presence of rotation. Thus, linear acceleration cues, not yaw rotational cues, appear necessary to simulate hovering flight.

2. LIST OF SYMBOLS

a_{x_p}	longitudinal acceleration at pilot station, ft/sec^2
a_{y_p}	lateral acceleration at pilot station, ft/sec^2
c.m.	vehicle center of mass
F(x,y)	F ratio with x numerator degrees-of-freedom and y denominator degrees-of-freedom
g	gravitational acceleration, ft/sec^2
h	altitude of c.m., ft
$\ddot{h}$	vertical acceleration of c.m., ft/sec^2
$\ddot{h}_{com}$	motion system vertical acceleration command, ft/sec^2
$\ddot{h}_{sim}$	motion system vertical acceleration, ft/sec^2
K	motion filter gain, nondimensional
K_y	vestibular model gain
rms	root mean square
s	complex variable, 1/sec
$\ddot{x}_{com}$	motion system longitudinal acceleration command, ft/sec^2
x_p	pilot longitudinal displacement from c.m., ft
$\ddot{x}_{sim}$	motion system longitudinal acceleration, ft/sec^2
$\ddot{y}_{com}$	motion system lateral acceleration command, ft/sec^2
$\ddot{y}_{sens}$	pilot sensed lateral acceleration, ft/sec^2
$\ddot{y}_{sim}$	motion system lateral acceleration, ft/sec^2
z_1	state for dynamic inflow approximation
δ_c	cockpit collective position, in
δ_r	cockpit pedal position, in
ζ	motion filter damping ratio, nondimensional
ψ	vehicle model yaw angle, rad
$\dot{\psi}$	vehicle model yaw angle rate, rad/sec
$\ddot{\psi}$	vehicle model yaw acceleration, rad/sec^2
$\ddot{\psi}_{com}$	motion system yaw acceleration command, rad/sec^2
$\ddot{\psi}_p$	yaw acceleration at pilot station, rad/sec^2
$\ddot{\psi}_{sens}$	pilot sensed yaw acceleration, rad/sec^2
$\ddot{\psi}_{sim}$	motion system yaw acceleration, rad/sec^2
ω	frequency, rad/sec
ω_m	motion filter natural frequency, rad/sec

3. INTRODUCTION

The question of whether or not a yaw rotational motion degree-of-freedom is necessary in flight simulation is important to government regulators, since they specify the simulator motions necessary for desired levels of simulator sophistication (Ref. 1). It is also important to simulator designers and operators, who build and/or configure how the motion system actuator displacements should be apportioned into the motion degrees-of-freedom.

Currently, the Federal Aviation Administration specifies two levels of motion fidelity for helicopter flight simulators: full 6-degrees-of-freedom motion, and 3-degrees-of-freedom motion (Ref. 1). For the latter, the assumed three degrees of freedom are pitch, roll, and vertical. If degrees of freedom different from these three are selected, these new selections must be qualified on a case-by-case basis. The selection of the pitch, roll, and vertical axes is reasonable and based upon experience, but evidence to support these axes or any set of axes is lacking.

Differences of opinion exist on the relative importance of rotational versus linear motion cues in the selection of critical axes. For example, the abstract of Reference 2 states that, for tracking, "translational motion cues appear to be generally less important than rotational ones, although linear motion can be significant in special situations." In contrast, the concluding remarks of Reference 3 state, "For large aircraft, due to size and to the basic nature of their maneuvering dynamics, the cockpit lateral acceleration cues appear to be much more important than roll acceleration cues. There was the indication that this observation might be extended to the generalization that, in each plane of motion, the linear cues are much more valuable than the rotational cues."

Most flight simulation studies focusing on the interactions between rotational and linear acceleration cues have been performed in the roll axis (Ref. 4). Roll-axis interactions are especially important for simulating turn coordination. For the yaw axis, work examining the usefulness of the associated cues has been sparse and not conclusive. Meiry, in the first detailed investigation into the effects of yaw motion, found that its addition was shown to be beneficial, as the study indicated a reduction in operator-time-delay of 100 msec, with a concomitant improvement in performance (Ref. 5).

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In contrast, two recent simulation studies that examined a pilot's ability to perform hovering flight tasks with a representative vehicle model found little or no effect of yaw on pilot performance or opinion (Refs. 6 and 7). However, in those studies, the pilots were intentionally located at the vehicle's center of rotation to study the effects of yaw motion only; thus, the typical accompanying lateral and longitudinal accelerations were absent by design. Those results suggested that simulator yaw motion may not be necessary for the tasks that simulate hovering flight.

The purpose of the study described here is to extend this previous work and determine what components of motion are important to include in flight simulation. Specifically, linear accelerations induced by yaw rotations, when the pilot is not at the center of rotation, were physically introduced to determine if the results from References 6 and 7 may be generalized into a hypothesis that yaw rotational simulator cab motion has no significant effect. If so, then a savings might result from a reduced level of complexity required in the design, development, and operation of flight simulators.

This paper is organized as follows. First, a brief discussion of human motion sensing characteristics is given in order to place the magnitude of the accelerations provided in this experiment in context. Second, the tasks and the experimental apparatus are described. Then, the measured pilot-vehicle performance, pilot control activity, pilot compensation, motion fidelity, and motion reports, are presented and discussed.

3.1 Human Lateral-Directional Motion Sensing

Perception of motion arises from a complex, and incompletely understood, interaction of visual, tactile, and vestibular stimuli. Of the two non-visual stimuli, the vestibular system has received the most attention.

In an extensive review, Peters (Ref. 8) found the following model, taken from Meiry (Ref. 2), to be the most reasonable characterization of the subjective perception of rotational acceleration about a vertical axis due to an excitation of the semi-circular canals in the inner ear:

$$\frac{\ddot{\psi}_{sens}}{\ddot{\psi}_{sim}} = \frac{10s}{(s+0.1)(s+10)} \tag{1}$$

Rotational acceleration thresholds of perception were also examined extensively in Reference 8. Of the 14 studies reviewed, a vertical axis rotational acceleration threshold range between 0.035 and 2.0 deg/sec^2 was found. Given those thresholds, pilots should have perceived the rotational accelerations in the study described herein, as the maximum rotational accelerations were typically 20 deg/sec^2, thus exceeding the maximum threshold above by an order of magnitude.

Dynamics of the utricles in the inner ear, which sense linear acceleration, are given in Reference 2 as:

$$\frac{\ddot{y}_{sens}}{\ddot{y}_{sim}} = \frac{K_y s}{(s+0.1)(s+1.5)} \tag{2}$$

The cutoff frequency of 1.5 rad/sec suggests that high-frequency accelerations must be sensed by the tactile mechanisms in the body and not the vestibular system. Reference 8 reviewed horizontal acceleration thresholds from seven sources, and found that they ranged between 0.002 and 0.023 g's. In the study described herein, the maximum lateral accelerations were typically 0.05 g's, which are more than double the above maximum threshold of perception.

The tasks discussed later will illustrate that the rotational and lateral accelerations that were generated were well above the published thresholds and at frequencies within the bandwidth of the dynamic models in eqns. 1 and 2.

4. EXPERIMENT DESCRIPTION

4.1 Tasks

NASA test pilots flew three tasks that represented a broad class of situations in which both linear and rotational motion cues may be useful in flight simulation. Task 1 was a small-amplitude command task that allowed for full math model motion to be provided by the motion system in the horizontal plane. Task 2 was a large-amplitude command task that did not allow full math-model motion to be presented (simulator cab rotational and longitudinal translational limits would have been exceeded), but was accompanied by strong rotational visual cues. Task 3 was a disturbance rejection task, which also allowed full math-model motion to be provided by the motion system, but with the pilot also controlling vehicle altitude.

Task 1: 15-deg yaw capture. For the first task, the pilot controlled the vehicle only in the yaw axis and was required to rapidly acquire a north heading from 15-deg yaw offsets to either the east or west. This task allowed for full math-model motion to be represented by the motion system in all axes (rotational, lateral, and longitudinal). An aircraft plan view, with the pilot's simulated position relative to the fixed c.m., is shown in Fig. 1. The desired pilot-vehicle performance for the task was to rapidly capture and stay within +/-1 deg about north with two overshoots or less. This 2 deg range was visually demarcated by the sides of a vertical pole, shown in his forward field-of-view in Fig. 2. Pilots performed six total captures for each configuration, alternating between initial west and east directions. The repositionings from north to the initial east or west directions were not part of the task.

Task 2: 180-hover turn. The second task was a 180-deg pedal turn over a runway performed in 10 sec. The pilot again controlled the aircraft with the pedals only, and the position of the c.m. remained fixed. This maneuver was taken from the current U.S. Army rotary-wing design standard (Ref. 9) and, with one proviso, is representative of a handling qualities maneuver performed for acceptance of military helicopters. In the military acceptance maneuver, the pilot controls all six degrees of freedom rather than one. This maneuver did not allow full math-model motion, since the simulator cab cannot rotate 180 degs. As a result, attenuated motion was used (see Section 4.4). Desired performance was to stabilize the complete turn within +/- 3 degs and within 10 secs. Pilots performed six 180-deg turns, always turning over the same side of the runway to keep the visual scene consistent for the set of turns. Figure 3 shows the visual scene from the starting position.

Task 3: yaw regulation The third task required the pilot to perform a rapid 9-ft climb while attempting to maintain a constant heading. This disturbance rejection task was challenging, because collective lever movement in the unaugmented AH-64 model results in a substantial yawing moment disturbance (due to engine torque) that must be countered (rejected) by the pilot with pedal inputs. This task allowed full vertical and yaw motion, and the pilot now had to control these two axes simultaneously. Desired performance was for the pilot to acquire the new height as quickly as possible while keeping the heading within +/-1 deg north. The same

visual scene was presented as in Task 1 (Fig. 2), but with the scene also indicating height variations as the vehicle model changed altitude.

4.2 Vehicle Dynamics
The math model represented an unaugmented AH-64 Apache helicopter in hover, which had been identified from flight test data and subsequently validated by several AH-64 pilots (Ref. 10). Equation 3 provides the vehicle dynamics for the yaw and vertical degrees-of-freedom.

$$\begin{bmatrix}\ddot{\psi}\\ \ddot{h}\\ \dot{z}_1\end{bmatrix}=\begin{bmatrix}-0.270 & 0.000 & 0.000\\ 0.000 & -0.122 & -118.\\ 0.000 & 0.000 & -12.9\end{bmatrix}\begin{bmatrix}\dot{\psi}\\ \dot{h}\\ z_1\end{bmatrix}+\begin{bmatrix}0.494 & 0.266\\ 0.000 & 14.6\\ 0.000 & 1.000\end{bmatrix}\begin{bmatrix}\delta_r\\ \delta_c\end{bmatrix} \tag{3}$$

All other vehicle states were kinematically related to the above dynamics. So, in effect, the vehicle c.m. was constrained to remain on a vertical axis fixed in space for all tasks. While the tail rotor in an actual helicopter causes both a side force and a moment about the c.m., only the moment was represented in this experiment, due to the fixed c.m. These vehicle constraints were introduced to simplify the number of motion sensations that had to be interpreted by the pilot. No coordination of the gravity vector was required, as it remained fixed relative to the pilot. No atmospheric turbulence was present in any of the tasks. The collective lever was used for Task 3 only.

The pilot was located 4.5 ft forward of the simulated c.m., which is representative of the AH-64 pilot location. Thus for this case, math model rotational accelerations are accompanied by lateral accelerations at the pilot station, and rotational rates are accompanied by longitudinal accelerations at the pilot station. That is, the accelerations at the pilot station in this experiment are:

$$a_{x_p} = -x_p\dot{\psi}^2 \tag{4}$$

$$a_{y_p} = x_p\ddot{\psi} \tag{5}$$

$$\ddot{\psi}_p = \ddot{\psi} \tag{6}$$

4.3 Simulator And Cockpit
The NASA Ames Vertical Motion Simulator (VMS) was used for this experiment (Ref. 11). The mainframe-computer cycle time was 25 msec. A cutaway view of the motion system and the experiment's software-command position, velocity, and acceleration limits are shown in Fig. 4. Within the listed limits, the dynamic performance of the simulator depends on the axis. Using frequency response testing techniques (Ref. 12), the dynamics of the yaw rotational, longitudinal, lateral, and vertical axes were fitted with equivalent time delays (that is, the phase response was approximated as a pure time delay) as shown below (eqns 8 and 9 are taken from Reference 13):

$$\frac{\ddot{\psi}_{sim}}{\ddot{\psi}_{com}}(s) \approx e^{-0.13s} \tag{7}$$

$$\frac{\ddot{x}_{sim}}{\ddot{x}_{com}}(s) \approx e^{-0.17s} \tag{8}$$

$$\frac{\ddot{y}_{sim}}{\ddot{y}_{com}}(s) \approx e^{-0.13s} \tag{9}$$

$$\frac{\ddot{h}_{sim}}{\ddot{h}_{com}}(s) \approx e^{-0.14s} \tag{10}$$

The Evans and Sutherland CT5A visual system was used to provide the out-the-window visual cues. The visual field-of-view is shown in Fig. 5, and it had a math-model-to-visual-image-generation delay of 86 msec (Ref. 14). The visual cues presented to the pilot did not vary with the motion filter configurations (see Section 4.4) and were always those of the math model. These cues represented his physical offset of 4.5 ft forward of the simulated vehicle c.m.

Conventional pedals and a left-hand collective lever were used. The pedals had a travel of +/- 2.7 in, a breakout force of 3.0 lb, a force gradient of 3 lb/in, and a damping ratio of 0.5. The collective had a travel of +/- 5 in, had no force gradient, and the friction was adjustable by the pilot.

All cockpit instruments were disabled, which made the visual scene and motion system cues the only primary cues available to the pilot. Rotor and transmission noises were present to mask the motion system noise. Six NASA Ames test pilots participated in Task 1, and five of the same six participated in tasks 2 and 3. All pilots had extensive rotorcraft flight and simulation experience.

4.4 Motion System Configurations
Four motion system configurations were examined for each task: 1) rotational and linear motion, 2) linear without rotational motion, 3) rotational without linear motion, and 4) no motion. Figure 6 illustrates, in a plan view, the simulator cab motion for these configurations for Task 1 (+/- 15 deg heading turns). In the Linear+Rotation case, the cab rotates and translates as if it were placed on the end of a 4.5 ft vector rotating in the horizontal plane. In the Linear case, the pilot always points in the same direction, as the cab translates in x and y. In the Rotation case, the cab rotates but does not translate. Finally, in the Motionless case, the cab does not move.

When either linear motion or rotational motion was present for Tasks 1 and 3, it was the full motion calculated by the vehicle math model. That is, the cockpit provided the full accelerations that the math model calculated and that the visual scene provided (along with the effective motion delays in eqns 7-10). This statement was true, except for the longitudinal motion provided by the Linear motion configuration. This was because for yaw turns about a point, the longitudinal acceleration at the pilot's station is always negative (centripetal acceleration in eqn. 4). These accelerations, if integrated twice to motion system position commands, would cause continual longitudinal cab movement aft for this motion configuration, which results in the simulator cab eventually exceeding its available longitudinal displacement. Thus, a second order, high-pass filter was used in the longitudinal axis so that the cab would return to its initial position in the steady state. This type filter is typically used in flight simulation, and it had the form of:

$$\frac{\ddot{x}_{com}}{a_{x_p}}(s) = \frac{Ks^2}{s^2 + 2\zeta\omega_m s + \omega_m^2} \tag{11}$$

As described earlier, Task 2 did not allow full motion. Thus, a high-pass filter of the same form in Eqn. 11 was used in all axes. The values of K and ω_m were empirically selected to use as much cockpit motion as available (Fig. 4). For Task 3, the vertical motion was always the full math model vertical motion, even in the "Motionless" condition. That is, "Motionless" for Task 3 refers to the simulator cab being motionless in

the horizontal plane. Table 1 lists K and ω_m for each tested configuration in each axis (a configuration with K=1 and ω_m =1.0E-5 rad/sec effectively makes the filter in equation 11 unity for the tasks). The filter damping ratio (ζ) was 0.7 for all configurations.

4.5 Procedure
Pilots were asked to rate the overall level of compensation required for a task using the following descriptors: not-a-factor, minimal, moderate, considerable, extensive, and maximum-tolerable. For analysis, these adjectives were given interval numerical values from 0 to 5. Next, the pilots rated the motion fidelity according to the following three categories: 1) Low Fidelity - motion cueing differences from actual flight were noticeable and objectionable, 2) Medium Fidelity - motion cueing differences from actual flight were perceptible, but not objectionable, and 3) High Fidelity - motion cues were close to those of actual flight. These definitions were taken and slightly modified from Reference 15. These subjective ratings were given numerical values 0 to 2, respectively. Third, pilots were asked to report whether or not they felt any motion in the lateral or rotational axis, or both. A zero was assigned if they did not feel motion in a given axis, and a one was assigned if they felt motion. Each of the four configurations was flown four times in a random sequence by each pilot.

5. RESULTS
The experimental design above is a two-factor fully within subjects factorial experiment (Ref. 16), with the two independent variables being linear and rotational motion. The combination of the two levels (motion present and motion absent) within each independent variable results in four configurations for each task. An analysis of variance on the data taken for each task was performed, with the observed significance levels (p-values) given below. The quantity F(x,y) is the ratio of the data variations between configurations to the variations within the configurations. The p-values represent the probability of making an error in stating that a difference exists based on the experimental results, when no difference actually exists. Typically, differences are deemed significant for $p<0.05$ (5 chances in 100 of making an error).

5.1 Task 1: 15-deg Yaw Capture

Full motion versus no-motion. Figure 7 shows a representative time history of several key variables for Task 1 for the Linear+Rotation motion condition. Peak yaw rates (not shown) for this run were consistently on the order of 10 deg/sec. Figure 8 shows the same variables for the same pilot, but with the Motionless configuration. When compared to the full-motion case in Fig. 7, this motionless case results in more yaw overshoots, higher math model accelerations, and larger control inputs. These general degradations are typical when all motion is removed and are consistent with previous data taken for the vertical axis (Ref. 7).

Pilot-vehicle stability Figure 9 depicts, for the four motion conditions, the means and standard deviations of the number of times pilots overshot the +/- 1 deg heading point about north. For instance, when no rotational and no linear motion was present (Motionless), the mean number of overshoots outside the +/- 1 deg point was 11 per run across the pilots. This measure is generally indicative of the level of damping (or stability) in the pilot-vehicle system. The analysis of variance for these results show that when linear motion was added, the decrease in the number of overshoots was statistically significant ($F(1,4)=9.16$, $p=0.039$). The decrease in overshoots with the addition of rotational motion was marginally significant here ($F(1,4)=5.58$, $p=0.077$). The effects of rotational and linear motion did not interact in this measure (i.e., were statistically independent).

Control rate. Figure 10 illustrates the rms cockpit control (pedal) rate for the four configurations. Often, this measure is associated with pilot workload, with more control rate being generally indicative of more pilot lead compensation required for a given task. The analysis of variance for these data shows when linear motion is added that the decrease in pedal rate is statistically significant ($F(1,4)=18.53$, $p=0.013$). No significant differences were noted when rotational motion was added, and rotational and linear motion effects did not interact.

Compensation ratings. Figure 11 shows the means and standard deviations of the compensation required, as rated by the pilots, for the four motion conditions. When linear motion was added, the compensation required significantly decreased from considerable to moderate compensation ($F(1,5)=6.83$, $p=0.047$) while no significant differences were found for the addition of rotational motion. Rotational and linear motion did not interact for pilot compensation. These subjective pilot opinions are consistent with the measured control rate differences just discussed. That is, the addition of linear motion reduced needed control activity, which in turn is generally related to the pilot compensation required.

Fidelity ratings. Similar results occurred for the pilots' rating of motion fidelity, as shown in Fig. 12. When linear motion was added, the motion fidelity rating improved ($F(1,5)=7.74$, $p=0.039$). The fidelity increased from low-to-medium to medium-to-high, on average. Again, no reliable differences were noted for the addition of rotational motion (the mean improvement shown when rotational motion was added without linear motion was not statistically significant). Rotational and linear motion did not interact in the fidelity ratings.

Lateral motion reports. Figure 13 depicts the mean percentage of the time pilots reported lateral motion to be present for the four motion configurations. Statistically, the two factors of rotational and linear motion interacted ($F(1,5)=30.6$, $p=0.003$). Lateral motion was reported an average of 85% of the time when it was present, and the addition of rotational motion did not increase lateral motion reports (actually, it decreased lateral motion reports from 91% to 79%). On the other hand, while lateral motion was never reported in the no motion condition, it was reported nearly 50% of the time when only rotational motion was present.

The influences of purely rotational cues on lateral motion reports could be due to the pilots sensing some true lateral acceleration. The pilot's design eye point was less than 0.5 ft forward of the motion system's rotation point. It is possible that, depending on the variation in pilots' posture, this small offset may have resulted in their vestibular system registering a linear acceleration. The maximum rotational accelerations for the likely worst case (0.5 ft offset and a 20 deg/sec^2 yaw accelerations, see Fig. 7) results in a 0.005-g linear acceleration. This acceleration is small but perhaps just within a pilot's threshold (see Section 3.1).

Rotational motion reports. Pilot reporting of rotational motion, shown in Fig. 14, was also affected by an interaction between actual rotational and linear motion ($F(1,5)=10.4$, $p=0.023$). Rotational motion was reported 30% of the time when no motion was present at all. The reporting of rotational motion increased dramatically to 87% when any motion, rotational, linear, or both was given. Apparently, when combined

with visual cues, the linear motion enhances the onset of vection.

To summarize the results for this task, linear motion was clearly the most important motion variable. Linear motion improved pilot-vehicle performance, lowered control activity, lowered pilot compensation, improved pilot impression of motion fidelity, and caused pilots to believe that rotational motion was present when it was not. Also, from the acceleration magnitudes involved, it is likely that it was the lateral component of the two linear motions that was effective. The addition of rotational motion showed no statistically significant improvement, with the exception of its effect on reporting when lateral motion is present, as possibly explained earlier.

5.2 Task 2: 180-deg Hover Turn

Full motion versus no-motion. Figure 15 is a representative time history of several key variables for the Linear+Rotation motion condition in Task 2. Peak math model and visual yaw rates for this turn were consistently on the order of 50 deg/sec (not shown). These rates were, of course, attenuated by the motion system (Table 1) so that it remained within its displacement constraints. Figure 16 shows the same variables for the same pilot for the Motionless configuration. An increase in yaw overshoots is noted, which is evident in the displacements, rates, accelerations, and control inputs. These trends are consistent with Task 1.

Pilot-vehicle stability. Figure 17 depicts, for the four motion conditions, the means and standard deviations of number of times pilots overshot the +/- 3 deg heading point about the runway centerline during the 180 deg turns. These results show that when linear motion was added, the decrease in the number of overshoots was marginally significant statistically ($F(1,4)=5.40$, $p=0.081$). Interestingly, in this case, the addition of rotational motion made the performance worse, and this result was statistically significant ($F(1,4)=13.26$, $p=0.022$). Rotational and linear motion did not interact in this measure. These results are not easily explained; however, it must be remembered that this task did not have full math model motion. So, a possibility is that some false cueing in rotation, due to the motion filter and its selected parameters, had a negative impact on performance in this case. On the other hand, the same false cueing would also be present at the same time in the lateral axis, since the same filter was used and the motion cues are proportionally related (eqn. 5).

Control rate. Figure 18 illustrates the rms cockpit control (pedal) rate for this task. The analysis of variance for these data indicated that the decrease in pedal rate was statistically significant for the two cases when linear motion was added ($F(1,4)=11.69$, $p=0.027$). No significant differences were noted when rotational motion was added, and linear and rotational motion effects did not interact.

Compensation ratings. Average pilot compensation required for this task is shown in Figure 19. Large variations in pilot opinion resulted. No statistically significant differences were noted; based upon the variation in the data, one cannot say that the motion configurations affected the subjective compensation required. However, the trends in Fig. 15 follow those in Task 1 (Fig. 11).

Fidelity ratings. Figure 20 shows the mean motion fidelity ratings for Task 2. Here motion fidelity was significantly higher when linear motion was present ($F(1,4)=47.9$, $p=0.002$), while the presence of rotational motion did not affect rated fidelity. Rotational and linear effects did not interact.

Lateral motion reports. Figure 21 illustrates the percentage of time pilots reported lateral motion being present. There were significantly more reports of lateral motion when it was present (70%), than when it was not (5%) ($F(1,4)=14.8$, $p=0.018$). There was no significant impact of rotational motion on lateral motion reports, nor was there any significant rotational motion and lateral motion interaction (unlike Task 1).

Rotational motion reports. In the reporting of rotational motion, the rotational and linear motion factors interacted (Fig. 22) ($F(1,4)=20.0$, $p=0.011$). Rotational motion was reported 90% of the time when linear motion was present, both when rotational motion was actually present and when it was absent. Only when linear motion was absent did the presence of rotational motion lead to increased reports of rotational motion. When no motion was presented, rotational reports occurred 27% of the time on average, but increased to 65% of the time when only an actual rotational motion was added.

To summarize the results for this task, linear (and therefore lateral) motion is again the key motion variable. Its addition reduced control activity, improved motion fidelity, and led to the belief that rotational motion was also present when it was not present. These results are similar to those of Task 1, except for the interesting result that the addition of rotational motion degraded performance slightly in Task 2.

5.3 Task 3: Yaw Regulation

Full motion versus no-motion. Figure 23 depicts key variables in a sample run for the Linear+Rotation condition in Task 3. The peak yaw rate for this run was 7.5 deg/sec (not shown). The peak yaw accelerations for this task were similar to those of Task 1, but the rms accelerations were slightly higher in Task 3 than Task 1 (5.67 deg/sec^2 versus 4.21 deg/sec^2, respectively). The amount of visual rotation was less in this disturbance rejection task than in the command task of Task 1. Figure 24 illustrates the same variables for the same pilot for the Motionless configuration Slightly more persistent acceleration overshoots are present when motion is removed.

Pilot-vehicle stability. Figure 25 depicts, for the four motion conditions, the means and standard deviations of number of times pilots had an excursion outside the +/- 1 deg heading about north per run. These results show that when linear motion was added, the decrease in the number of overshoots was statistically significant ($F(1,4)=8.06$, $p=0.047$). The addition of rotational motion did not yield a significant difference. The effects of rotational and linear motion did not interact in this measure.

Control rate. Figure 26 illustrates the cockpit control (pedal) rate for the four configurations. Unlike the previous two tasks, the addition of linear motion did not significantly reduce the rms pedal rate. However, the addition of rotational motion actually increased pedal rate ($F(1,4)=18.74$, $p=0.012$). The rotational and linear motion effects did not interact. So, this is another case where the addition of rotational motion made matters worse; however, as Fig. 26 shows, the percentage increase in control rate was not dramatic.

Compensation ratings. Average pilot compensation ratings are shown in Fig. 27. The improvement in the ratings for the linear motion conditions, relative to those in the rotational motion conditions, was marginally significant ($F(1,4)=6.38$, $p=0.065$). The addition of rotational motion resulted in no

statistical difference in compensation. The effects of rotational and linear motion did not interact.

Fidelity ratings. The same result occurred for rated fidelity, which is presented in Fig. 28. The addition of linear motion resulted in an improvement in fidelity ratings that was marginally significant ($F(1,4)=6.15$, $p=0.068$). The addition of rotational motion again made no difference. The effects of rotational and linear motion were statistically independent.

Lateral motion reports. Figure 29 illustrates the percentage of the time pilots reported lateral motion present. The addition of linear motion significantly increased the reports of lateral motion ($F(1,4)=12.1$, $p=0.025$). Interestingly, the addition of rotational motion led to a marginally significant decrease in the reports of lateral motion ($F(1,4)=5.4$, $p=0.08$).

Rotational motion reports. Figure 30 illustrates the percentage of the time pilots reported rotational motion was present. No significant effects were found, with rotation being reported an average of 73% of the time, independent of the motion configuration.

Summarizing the results of this task does not reveal differences from Tasks 1 or 2. Linear (lateral) motion was again the dominant variable. Its addition improved pilot-vehicle performance; although its effect upon rated pilot compensation and fidelity was less reliable than in the other two tasks. The only statistically significant effect of rotation was a deleterious effect on control activity.

5.4 Combined Results

Table 2 presents a summarizes the effects of the presence of lateral or yaw rotational motion on the six measurables for the three tasks. All of the improvements in the measures occur for the presence of lateral motion except for one. In that single case, a marginally significant effect was noted in pilot-vehicle stability for the addition of yaw rotation. Statistically significant degradations in the measures occurred only for the addition of yaw motion. Interactions between lateral and yaw rotational motion occurred only in the lateral and rotational motion perception reporting. However, in Tasks 1, 2, and 3, pilots reported (on average) rotational motion being present 87%, 90%, and 80% of the time when only lateral motion was present, respectively.

6. CONCLUSIONS

Three tasks were performed with a high-fidelity AH-64 helicopter hover mathematical model in the NASA Ames Vertical Motion Simulator to determine the importance of yaw rotational motion. Three tasks were selected to cover a range of situations often encountered in flight simulation. Pilot opinions of the compensation required to perform the task, the overall motion fidelity, and their ability to sense motion in all axes were collected.

The results indicate that for all tasks the addition of linear motion improved pilot-vehicle performance, reduced pilot compensation, improved pilot subjective impression of fidelity, and usually reduced control activity. Furthermore, the addition of lateral motion gave the pilots a strong sensation of both rotational and lateral motion being present.

On the other hand, the addition of rotational motion did not contribute to the improvement of pilot-vehicle performance, control activity, subjectively rated compensation, or subjectively rated motion fidelity. The presence of rotational motion led to a weaker sensation of rotational and lateral motion.

These results lead to the conclusion that for hover flight simulation, one should make every attempt to represent the linear lateral acceleration cue, as it is important to all the key aspects of pilot-vehicle performance and pilot opinion. In contrast, the presence of rotational motion about the vertical axis does not seem to provide significant, if any, value.

Thus, the yaw rotational motion degree of freedom in hovering flight simulation may not be necessary. The combination of lateral motion with a compelling visual scene may be all that is needed to make pilots perceive that physical yaw rotational motion is present.

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16. Mendenhall, W. and Sincich, T., *Statistics for Engineering and the Sciences,* Dellen Publishing Company, San Francisco, 1992, pp. 653-657.

Table 1 - Motion filter quantities for all tasks

Task	Rotation K	Rotation ω_m (rad/sec)	Lateral K	Lateral ω_m (rad/sec)	Longitudinal K	Longitudinal ω_m (rad/sec)	Vertical K	Vertical ω_m (rad/sec)
1 - linear+rot.	1.00	1.0E-5	1.00	1.0E-5	1.00	1.0E-5	0.00	1.0E-5
1 - linear	0.00	1.0E-5	1.00	1.0E-5	1.00	0.2	0.00	1.0E-5
1 - rot.	1.00	1.0E-5	0.00	1.0E-5	0.00	1.0E-5	0.00	1.0E-5
1 - motionless	0.00	1.0E-5	0.00	1.0E-5	0.00	1.0E-5	0.00	1.0E-5
2 - linear+rot.	0.35	0.55	0.35	0.55	0.35	0.55	0.00	1.0E-5
2 - linear	0.00	0.55	0.35	0.55	0.35	0.55	0.00	1.0E-5
2 - rot.	0.35	0.55	0.00	0.55	0.00	0.55	0.00	1.0E-5
2 - motionless	0.00	0.55	0.00	0.55	0.00	0.55	0.00	1.0E-5
3 - linear+rot.	1.00	1.0E-5	1.00	1.0E-5	1.00	1.0E-5	1.00	1.0E-5
3 - linear	0.00	1.0E-5	1.00	1.0E-5	1.00	0.2	1.00	1.0E-5
3 - rot.	1.00	1.0E-5	0.00	1.0E-5	0.00	1.0E-5	1.00	1.0E-5
3 - motionless	0.00	1.0E-5	0.00	1.0E-5	0.00	1.0E-5	1.00	1.0E-5

Table 2 - Summary of results

Measure	Lateral Task: 1	Lateral 2	Lateral 3	Rotational 1	Rotational 2	Rotational 3	Lat/Rot Interaction 1	Lat/Rot Interaction 2	Lat/Rot Interaction 3
Pilot-vehicle stability	**+**	+	**+**	+	-	o			
Control rate	**+**	**+**	o	o	o	-			
Compensation	**+**	o	+	o	o	o			
Fidelity	**+**	**+**	+	o	o	o			
Lateral reporting		**+**	**+**		o	-	x		
Rotational reporting			o			o	x	x	

+: Significant improvement; +: Marginal improvement; -: Significant degradation
o: No effect; x: Interaction

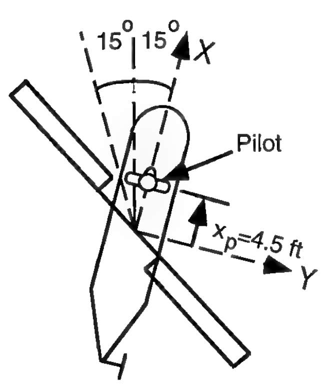


Figure 1 - Task 1 plan view.

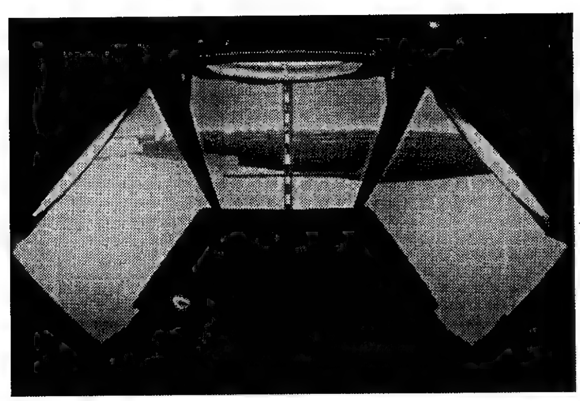


Figure 2 - Visual scene for tasks 1 and 3.

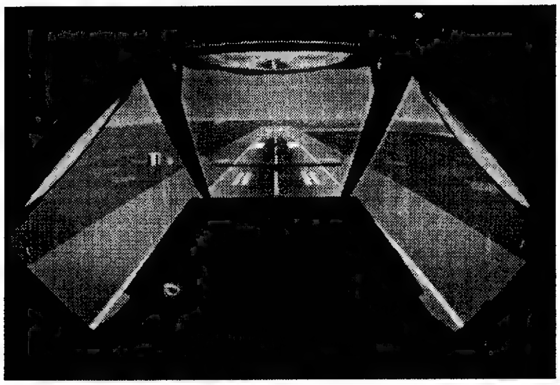


Figure 3 - Visual scene for task 2

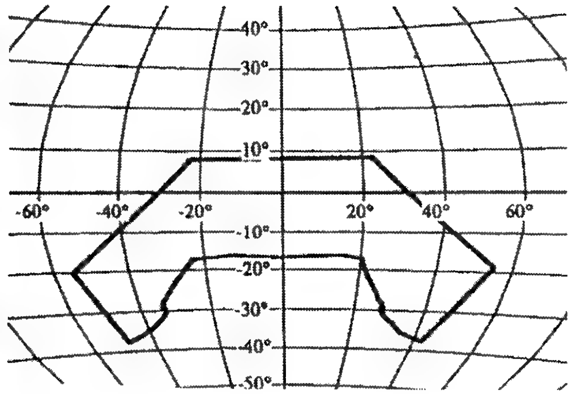
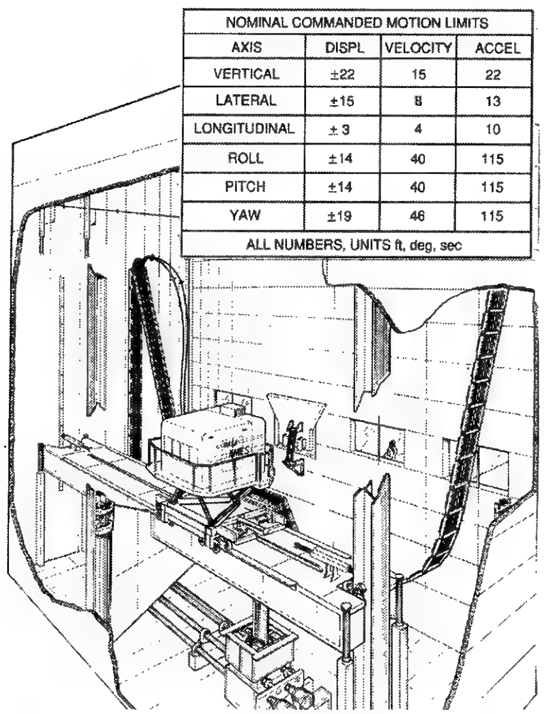


Figure 5 - Visual field-of-view



NOMINAL COMMANDED MOTION LIMITS			
AXIS	DISPL	VELOCITY	ACCEL
VERTICAL	±22	15	22
LATERAL	±15	8	13
LONGITUDINAL	± 3	4	10
ROLL	±14	40	115
PITCH	±14	40	115
YAW	±19	46	115
ALL NUMBERS, UNITS ft, deg, sec			

Figure 4 - Vertical Motion Simulator

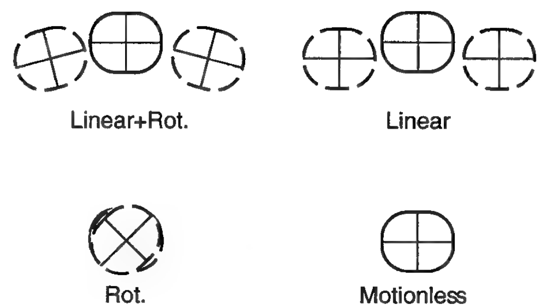


Figure 6 - Simulator cockpit motion for motion configurations in Task 1.

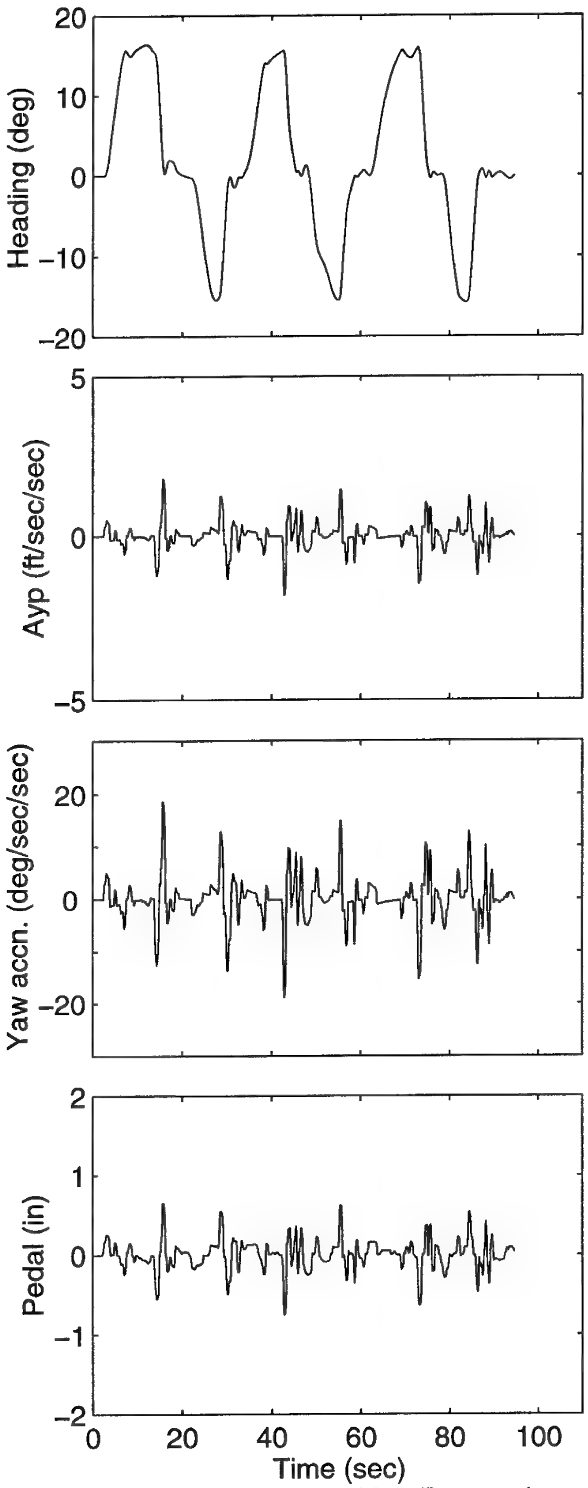


Figure 7 – Task 1, Lin.+Rot. motion

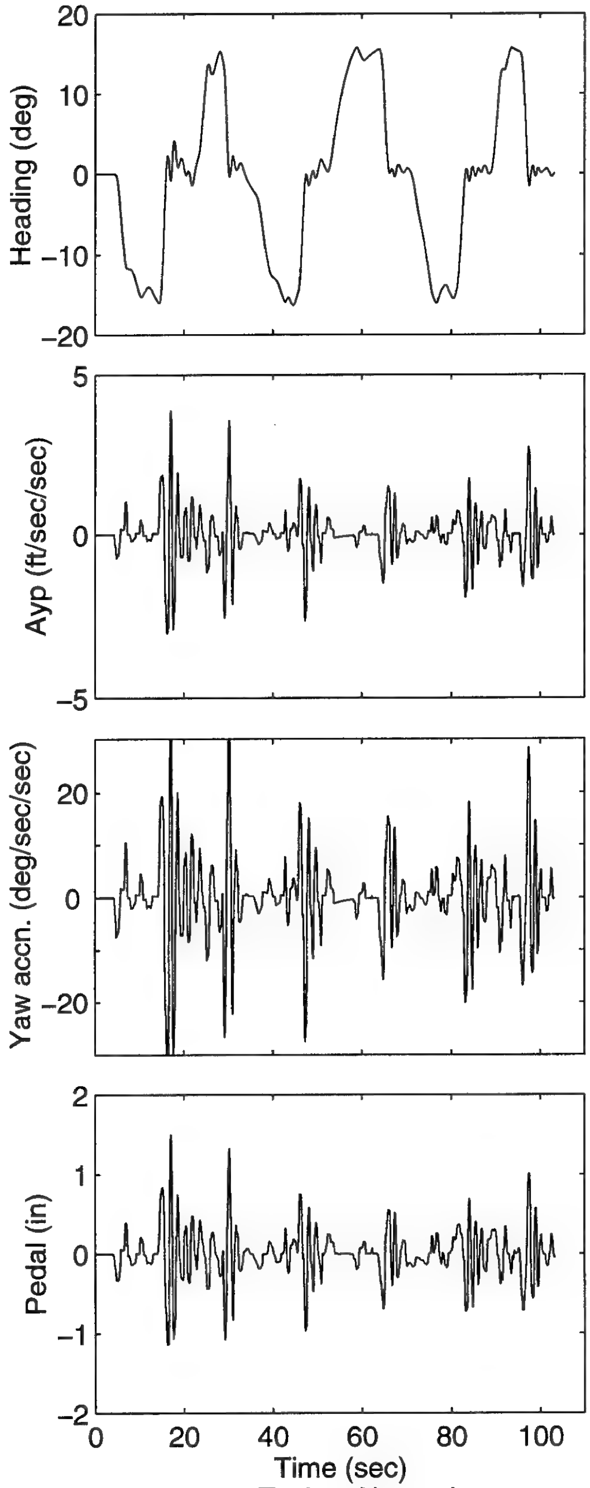


Figure 8 – Task 1, No motion

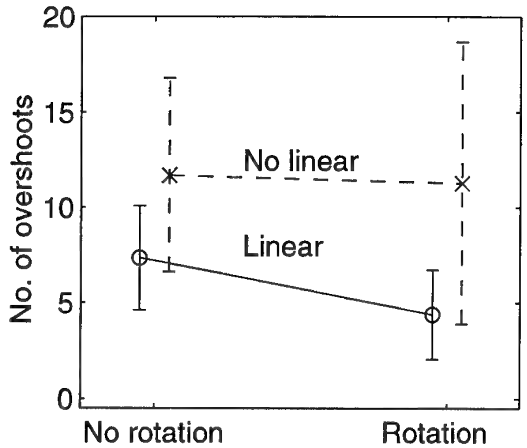


Fig. 9 – Measured Perf., Task 1

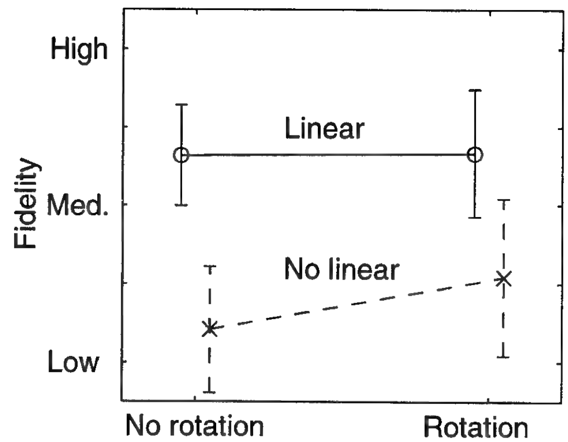


Fig. 12 – Motion fidelity, Task 1

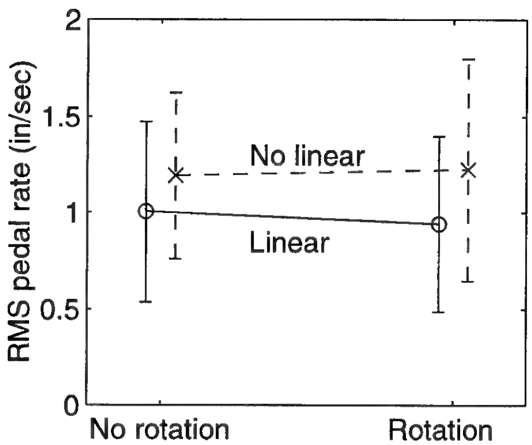


Fig. 10 – Control rate, Task 1

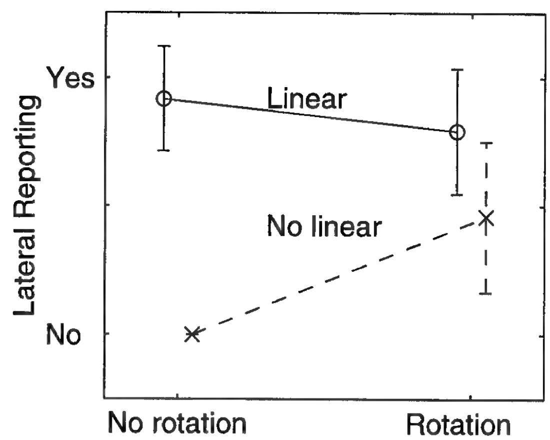


Fig. 13 – Lat. Motion Perception, Task 1

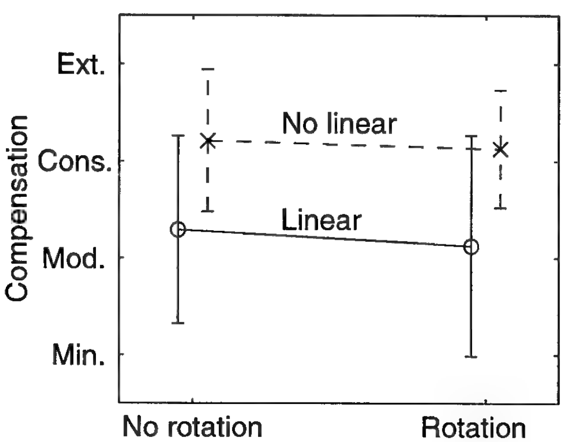


Fig. 11 – Pilot Comp., Task 1

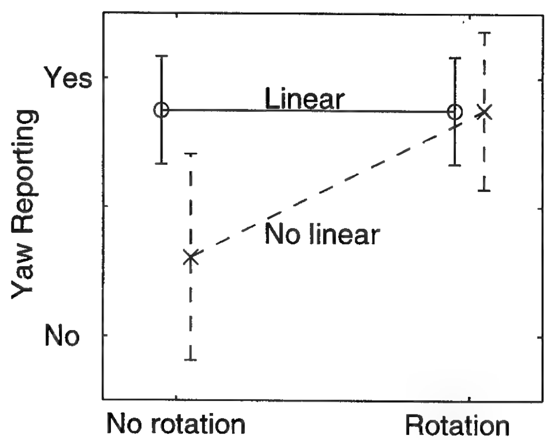


Fig. 14 – Rot. Motion Perception, Task 1

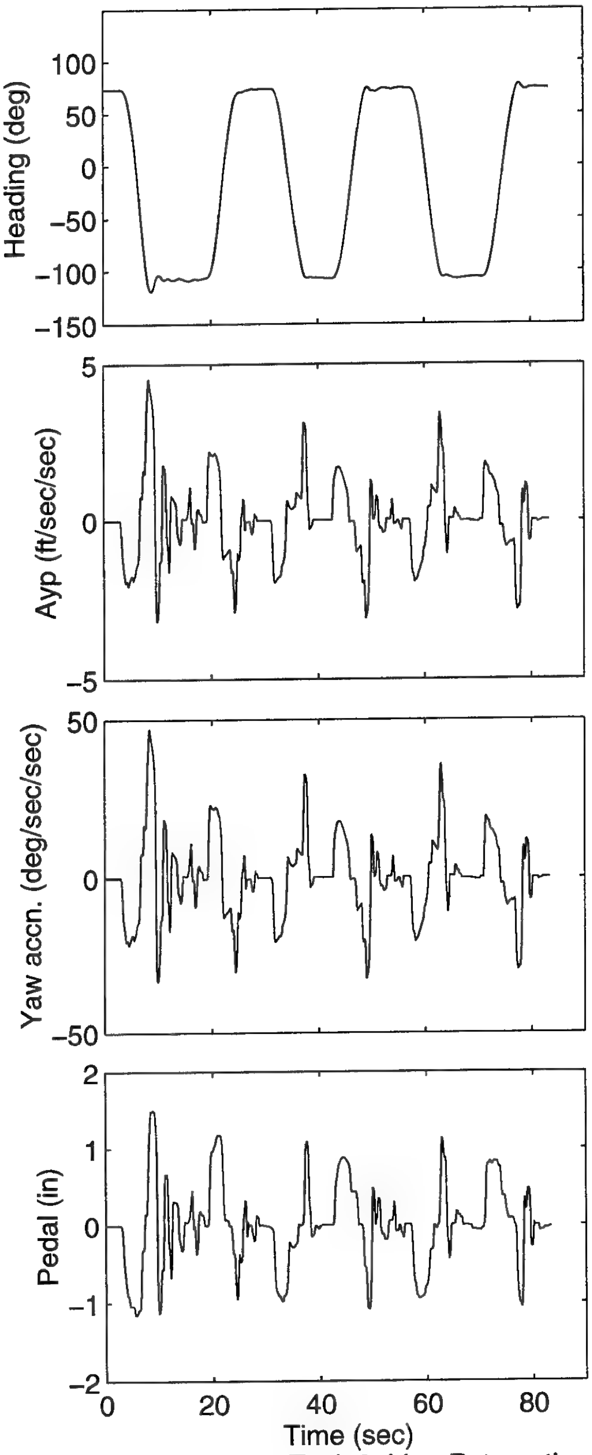


Figure 15 – Task 2, Lin.+Rot. motion

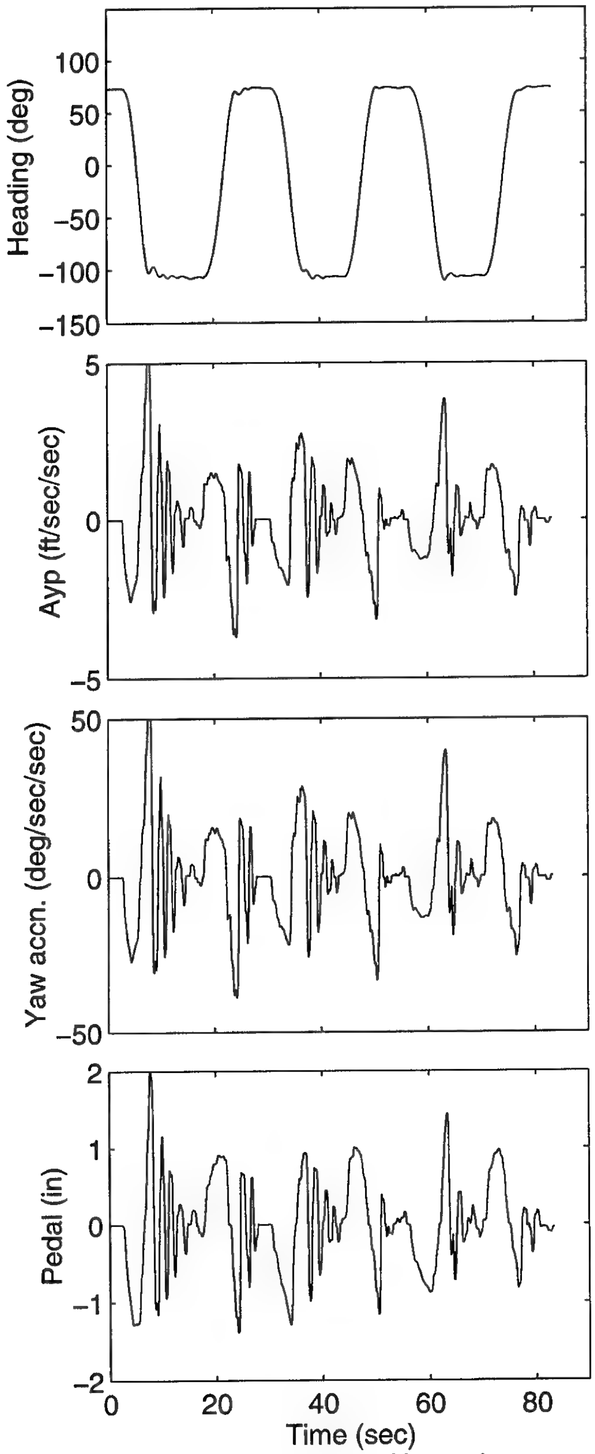


Figure 16 – Task 2, No motion

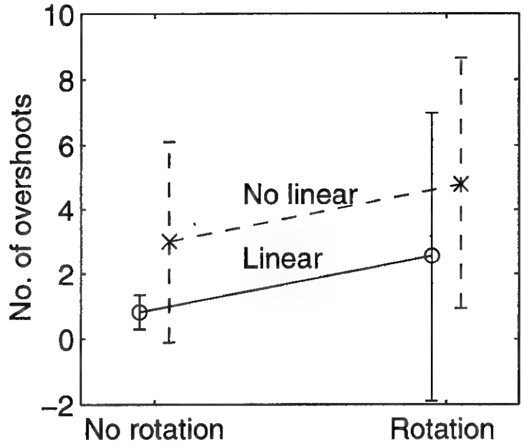


Fig. 17 – Measured Perf., Task 2

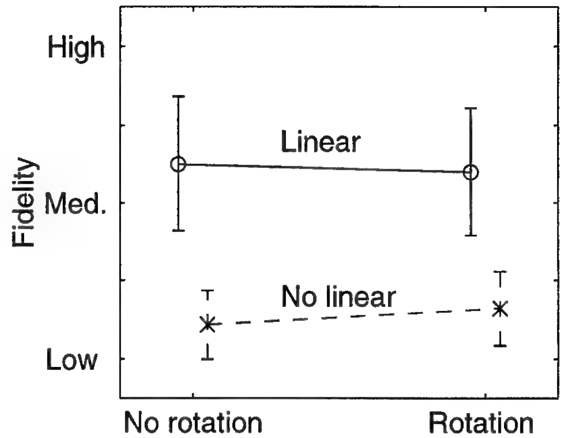


Fig. 20 – Motion fidelity, Task 2

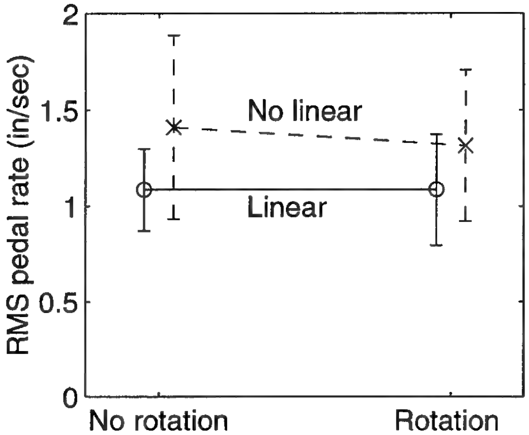


Fig. 18 – Control rate, Task 2

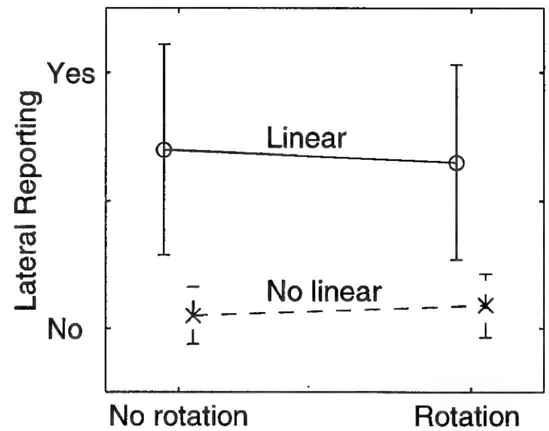


Fig. 21 – Lat. Motion Perception, Task 2

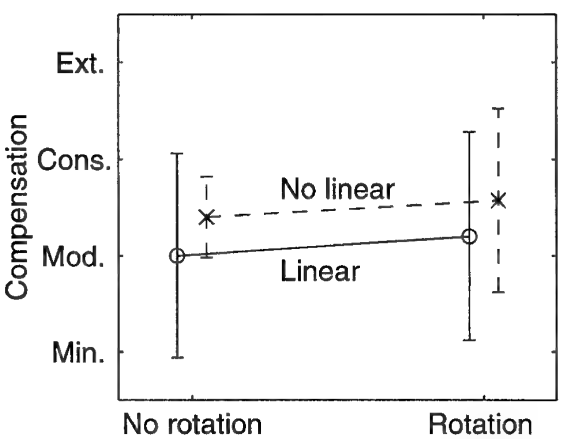


Fig. 19 – Pilot Comp., Task 2

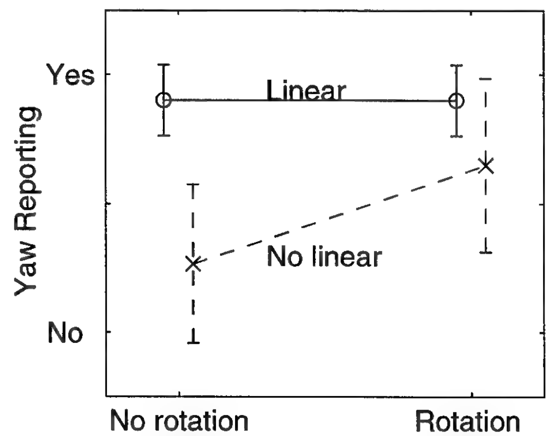


Fig. 22 – Rot. Motion Perception, Task 2

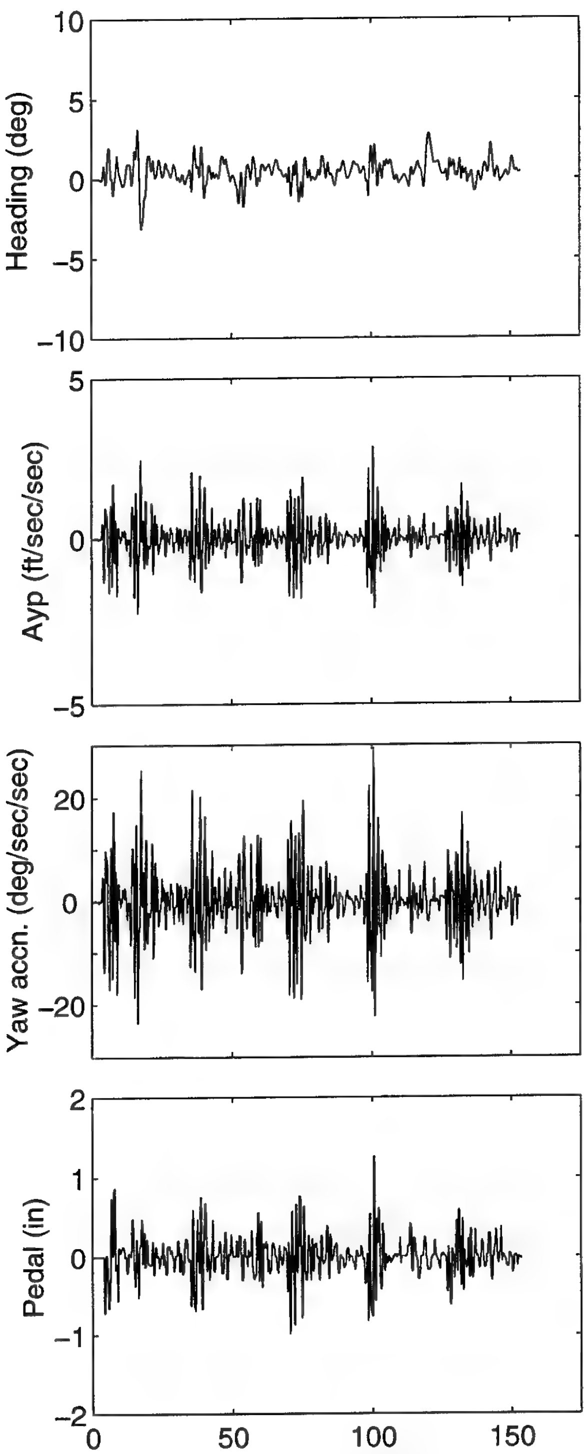


Figure 23 – Task 3, Lin.+Rot. motion

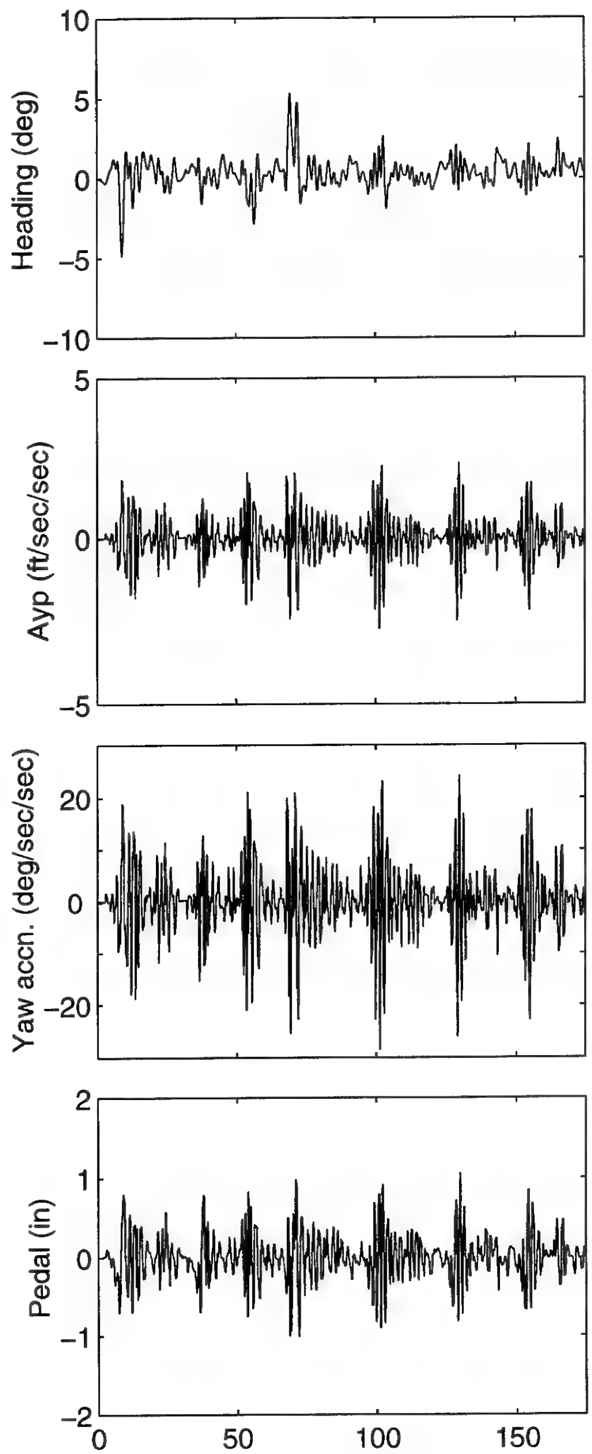


Figure 24 – Task 3, No motion

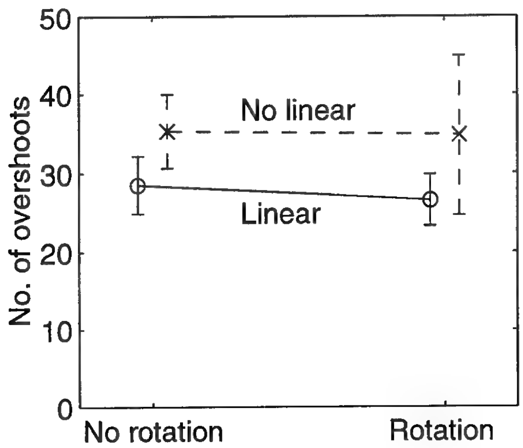


Fig. 25 – Measured Perf., Task 3

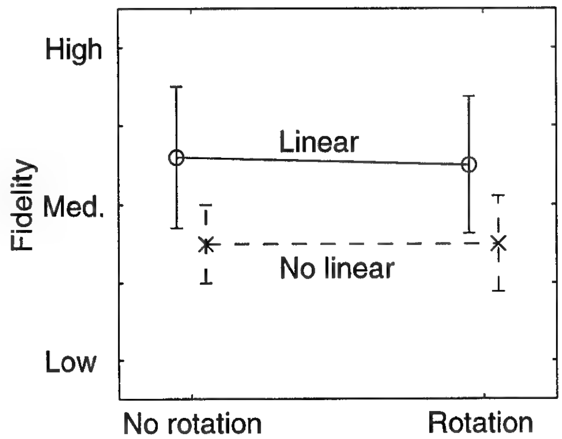


Fig. 28 – Motion fidelity, Task 3

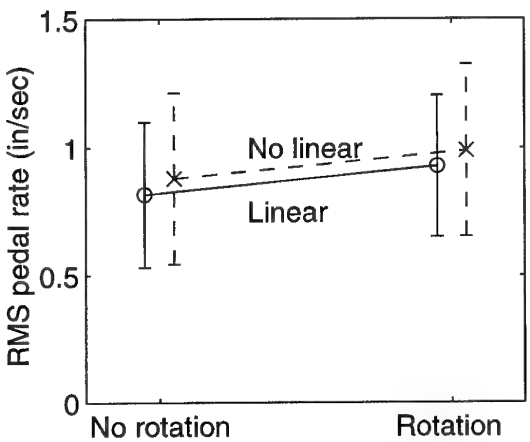


Fig. 26 – Control rate, Task 3

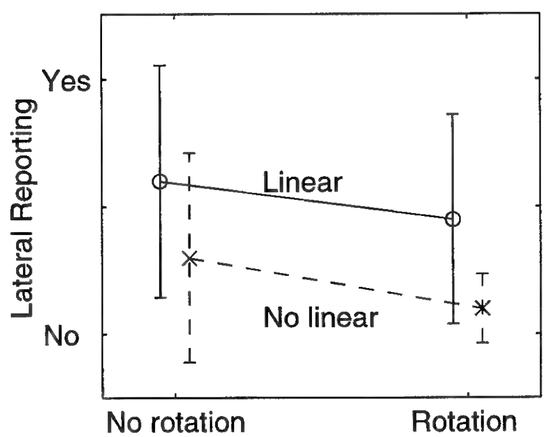


Fig. 29 – Lat. Motion Perception, Task 3

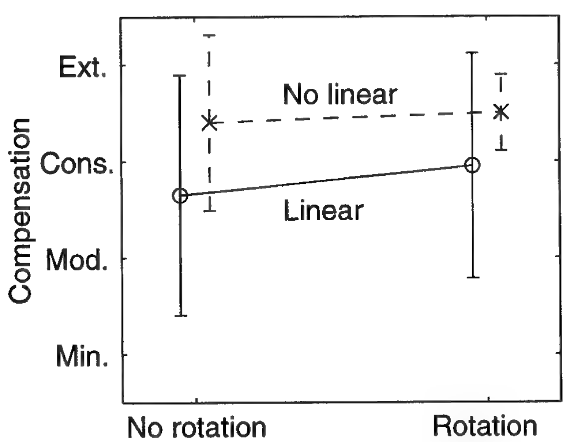


Fig. 27 – Pilot Comp., Task 3

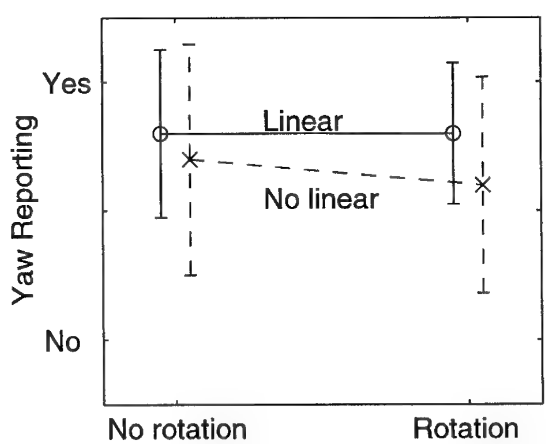


Fig. 30 – Rot. Motion Perception, Task 3

Achieving High-Fidelity Motion Cues in Flight Simulation

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Abstract

The simulation of high-bandwidth manual flight control tasks dictate the use of simulator motion systems for the reproduction of motion cues on the vestibular and neuromuscular-mechanical arm-manipulator system. The reproduction of these cues, with particular emphasis on the lowest possible time delay, is necessary in human perception research, experimental flight control system development studies, as well as in routine flight training. Perfect reproduction of motion cues with ground-based flight simulators is principally impossible due to the kinematic limitations inherent to the motion system. Washout filters minimize these effects. The dynamic characteristics of the motion system however lead to two types of control errors: *short-term*, due to finite oil stiffness and line dynamics, as well as limited control valve bandwidth, and *long-term*, due to complexity of the non-linear motion system dynamics, making compensation of unwanted parasitic errors difficult. This paper will review techniques which increase the performance of six-degrees-of-freedom hydraulic motion systems for flight simulators. Application of pressure-feedback actuator control increases the robustness of the motion system dynamics, hence decreasing the short-term errors. The long-term control errors are addressed by a (separate) robust, multi-variable motion system controller which provides control signals to the platform with knowledge of the system state and its inherent properties. The total mass and the vertical location of the centre of gravity of the platform influence the time delay (phase lag) and fidelity of the motion system. These properties also limit any such improvements due to design changes in software or hydraulic hardware. As a result of these studies, a fundamentally unique light-weight motion platform design is proposed, making extensive use of advanced composite materials. This is called the SIMONA Research Simulator. With the improvements made to motion cue quality, fundamental research into human perception processes in human perception research, and experimental flight control system development work, will not be influenced by parasitic motions.

Nomenclature

F_{ext}	external force
K_q	position error gain
$K_{\Delta P}$	pressure diff'l feedback gain
$K_c(s)$	control signal gain (time varying)
K_{vel}	velocity feedback gain
M	mass of actuator load
Pos. fb.	position feedback
Press. fb.	pressure feedback
q_d	demanded actuator position
q	measured actuator position
s	Laplace operator
u	valve input signal
ΔP	pressure differential
ε	error
Φ_o	valve supply flow

Introduction

The essential purpose of piloted flight simulators is to reproduce the physical and environmental cues as closely as possible to those encountered in flight. These cues result from control inputs exercised by the pilot, and are also due to external disturbances acting upon the vehicle. The pilot-vehicle interaction forms a closed loop in which the pilot receives information about the state, and change in state of the vehicle, through the sensory organs. The visual information is obtained through the foveal and central vision, while motion cues are derived from the visual and the vestibular system. These stimuli are processed by the brain, which can be thought of as to compare all the signals to an internally-developed model. In order for the response of two "similar" systems to match (hence, implying the fidelity of the simulation), the input signals must correspond with the aircraft specific forces and angular accelerations[1] at the pilot head position.

In human control tasks, visual information requires longer processing time than the vestibular cues. In other words, the onset of motion is primarily detected by the vestibular system, while long-term changes in motion are sensed predominately by the eyes [2]. This requires that the initial response of the simulator motion system matches that of the vehicle being simulated. This "onset cue" often

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includes the high-frequency components. In an ideal situation, the latency of the simulator above that of the vehicle dynamics should be close to zero, over the entire frequency range of the vehicle motion. This applies for the presentation of motion cues in particular. In practice, this is not easily achieved, mainly due to the limitations in the mechanical hardware and motion control software which induce the sensation of motions to the pilots. Host processor speed and vehicle model complexity limit the update rate of the state vectors. This report will however focus on the motion system alone and suggest means to improve its properties.

Current simulator requirements, such as those established by the United States Federal Aviation Administration stipulate that the motion response should precede all others, and that the total latency not exceed 150 milliseconds[3] (for Level-D training simulators). It is the aim of the present research to significantly reduce this figure, and maintain a very high level of fidelity with the required responses.

At the Delft University of Technology, the International Centre for Research in Simulation, Motion and Navigation Technologies SIMONA[4] is investigating the fundamentals of motion system dynamics, and proposing approaches to reduce latency and increase the bandwidth of current systems. A number of critical areas are addressed, which will be reviewed in this paper, namely:

- Motion platform dynamics as a function of mass properties
- Actuator control laws and shortcomings in high frequency control
- Platform control laws
- Platform design concepts to reduce inertial properties

Motion System Frequency Response and its Value on Simulation

It is fortunate that for control tasks the specific forces and angular accelerations need be presented as motion cues to the pilot (rather than absolute magnitudes of acceleration) [2]. Due to the high-frequency nature of the human vestibular sensors however, the quality of the responses, namely their temporal characteristics such as delay and phase, should be reproduced with little deviation from reality. The critical requirement of a motion system is to provide a given acceleration at the pilot position such that the onset of this motion is presented with a minimal delay. This should be made possible over a wide frequency range, preferably beyond those fundamentally required for the vehicle dynamics. The pilot position experiences frequencies through the audible range, however for the purposes of motion systems, one should try to address a cutoff frequency of approximately 15 Hz for most vehicles. It can be shown from flight tests that aircraft encounter excitations with frequency components in excess of 15 Hz. These can lead to sharp accelerations at the pilot position.

In order to realize higher performance (and hence higher fidelity) than current motion systems, a number of issues must be addressed. The frequency response of the simulator motion platform can be shown from experimental measurements[5], as well as from dynamic models which simulate the hydraulic, mechanical and electrical control feedback system properties. The latter has the advantage of being able to indicate the parameters to which the motion quality is most sensitive.

A study to investigate the sensitivity of the moving platform to variations in payload mass properties was conducted[6,7]. A complete non-linear simulation model of a synergistic six-degrees-of-freedom motion system[8] was used to evaluate the effects of platform inertia on the total dynamic behaviour[9, 10]. This model includes all hydraulic and mechanical properties of the motion system, as well as inertial properties of the payload mass and the actuators. All model elements are developed as discrete systems which are free of internal feedback couplings, similar to the construction of the actual simulator hardware. These are also joined in a data flow architecture representing the mechanical system structure.

The major components of the motion system in this simulation model include the mechanical system, including the moving and fixed platforms, hydraulic system, including the power supply system, servo valves, actuator hydraulics, and electronic system, including the computers, actuator controllers, transducers, filters and safety systems

A functional diagram of the simulation math model is shown in Figure 1.

Dynamic Simulations

The model described above, once validated with reasonable reliability[8], was used to assess the response of the motion platform. Figure 2 shows the response of a simulator platform resulting from a 0.5 m/s^2 step acceleration in the surge (X) direction, while the total platform mass is varied between 2000 and 18000 kilograms. (Note that a typical full flight simulator may have a mass up to 18000 kg). The mass distribution is assumed uniform and throughout a sphere with a radius of

3.0 m. In the figure shown, the centre of gravity is established at the centroid of the upper gimbal plane. Since the total load acting on the actuators is a function of the payload mass, this result implies the control system requirements. A significant decrease in the system natural frequency, and increase in damping, as would be expected, results from increasing payload. Most notably, the onset of the motion is delayed; as payloads increase, the desired acceleration level is delayed significantly.

A second set of results shows the influence of the centre of gravity location on the surge response. In this case, a fixed mass of 2000 kg is assumed for the platform. Variations in the centre of gravity, which in surge acceleration inputs influence the dynamic contribution load on the actuators, yield the results in Figure 3. Note that the onset acceleration delay is not significantly affected by these variations. The centre of gravity vertical location does, however, cause a simultaneous decrease in **both** the damping and the natural frequency. This rate of decrease appears, from this study, to be reasonably linear and can be attributed to the virtual mass (and not the real mass), caused by the dynamic load on the actuators. Unlike a true increase in the gross moving mass, the increase in the vertical offset in the centre of gravity increases a moment coupling effect, hence increasing the load on the actuators.

Figure 4, shows the platform response to a rotational acceleration in pitch. The same is shown for roll motions in Figure 5. Again, a lower mass yields more favourable properties in terms of the initial response and natural frequency.

As one would expect, the above results suggest that the motion system response is indeed sensitive to the load on the actuators. Any form of control should take into account that these loads may vary not only throughout the envelope, and as a result of variations in the platform mass properties. As a result, the actuator control, platform control and the design of the motion platform itself should be carefully considered. This is further explained in the following discussion.

Actuator Control of Short-Term Errors

High-performance motion system actuators must provide the required acceleration regardless of their actual loads and internal properties. This demand increases the required performance of the actuator controller in order that wide frequency ranges can be presented. The control strategy therefore shifts towards high-frequency force control loops, i.e. providing pressure control, rather than the conventional mid-frequency position-based servo control loops[11,12]. These high frequencies become increasingly relevant in long-stroke actuators due to transmission line effects. In most flight simulator motion systems, long-stroke (1 m or more) actuators are incorporated.

High-performance actuation will also require that the effects of parameter uncertainties and system variations be minimized through the application of robust control. Some practical examples of these phenomena are:

- dynamic variations in actuator loads throughout the operational envelope (including dynamic coupling due to the presence of large cable bundles)
- variations in static loads (hardware configurations, number of on-board occupants)
- internal system variations: leakage flows associated with hydrostatic bearings, oil temperature fluctuations, degraded (contaminated) servo valve performance, contaminated oil

With increased performance, robustness in a motion system can also reduce its maintenance time.

Platform Control of Long-Term Errors

The compensation of inertial effects related to the motion system dynamics is also necessary. Whereas the actuator-level controller compensates for each individual actuator, a higher-level system controller should compensate for the entire platform system dynamics. This may involve a combination of dynamic modelling, prediction, and feed-forward of the system response, and the communication of the required platform position to the actuator-level controllers.

Inertial Properties of the Motion Platform

Finally, the platform inertial properties should afford a minimal level of required compensation from the control system. It can be shown that the dynamic load variations on actuators can vary by an order of magnitude[13], and these variations can limit the eventual performance of the entire system. Therefore, a practical means of reducing the effective actuator loads should be sought. The eventual solution should also provide a platform with a stiffness greater than or equal to the control system frequency range, in order that the maximum performance is achieved. Note also that the actuators themselves should have inherent natural frequencies in this range.

From the above results (Figures 2 to 5), reductions in the platform mass and vertical location of the centre of mass can better the inherent characteristics of the motion system. The system natural frequency in particular appears to benefit directly from these properties.

Realizing High-Fidelity Motion Cues

The Delft University of Technology is investing major efforts to improve and demonstrate motion system performance in its new SIMONA Research Simulator. The SIMONA program will, among other issues, address all areas of the motion system design and control, to develop new strategies which will significantly improve time response characteristics. The remaining discussion in this paper will present the proposed scheme, review recent developments, and suggest the advantages to this approach at improving the response of a research simulator.

The SIMONA approach to high-performance motion systems involves a multi-level approach where the problem is initially defined by the type of control necessary. The motion control problem begins after the motion washout signals are generated by the host computer. These yield the desired state of the simulator actuators, and request this response from the Motion System Controller, as shown in Figure 6.

Multivariable Six-Degrees-of-Freedom Motion System Controller

This high-level control system, with inherent knowledge of the motion platform and hydraulic drive system properties, knows then the current state of the platform, and predicts the future state prior to generatinga command signal, thereby allowing refinement to the actuator-level input signals.

The hydraulic actuators in fact become "white boxes", with their state of operation being fully known by the 6 DOF controller. Thus, a general controller is developed to account for the reflected masses encountered on each motor, and which compensates for all instantaneous interactive loads.

A first approach will investigate linear and nonlinear multivariable strategies for motion platform control to compensate for platform loads and dynamics.

In a second approach, while the simulator is in use, a parallel model of its dynamics is run in real-time. This model is driven by the same signals which drive the motion system actuators, and measures the actual load on the motion system. Feed-forward control implemented in the parallel model can then be applied to the motion platform, providing a deterministic outcome

Robust Actuator Controller

Improving the total performance of the motion system requires also that the actuator-level controller be addressed. During an analysis into the impact of transmission line effects coupled with hydraulic control system dynamics, Schothorst[14] shows that severe stability problems may occur in some combinations when aiming for high-performance control, particularly when long-stroke actuators are involved*. First, consider that in most hydraulic servo control applications, a combination of classical feedback plus a damping loop, employing either pressure or acceleration feedback[12] is used. Highly reliable pressure difference transducers (PDT) are usually preferred over more expensive acceleration sensors. For practical purposes, PDT's are usually placed close to the valve. The actuator system model developed by Schothorst show the stability problem encountered in an open-loop** frequency response, Figure 7. Experiments by the same author have reproduced this phenomena, and it is suggested that a combination of transmission line dynamics (i.e. their resonance peaks) and the 180° phase shift associated with the valve dynamics cause the pressure feedback problems. This can be shown by removing the valve dynamics contribution from the model, and is shown by the dashed line in Figure 7.

Schothorst et al [14] propose that the solution to achieving stability in high-performance systems lies in a combination of the following factors:

- Choice of the most suitable feedback signal, such as the pressure difference at the actuator orifices, rather than at the servo valve (thereby eliminating the transmission line dynamics within this critical feedback signal).

- Choice of the servo valve, since the valve properties limit the allowable pressure feedback gains.

- Application of short transmission lines, to maintain the resonance modes in the very high frequency ranges.

- Advanced control design for pressure feedback loops, such as digital filters for the feedback signals. Robust control can provide tradeoffs between stability robustness and performance.

Robustness in actuator control loops

Traditionally, hydraulic servo control systems have incorporated proportional position feedback loops. These are coupled with the desired positions, which are double integrations of the desired accelerations resulting from unbalanced forces in the vehicle dynamics filtered through the motion washout algorithms. Note that a platform-to-actuator axis transformation resolves the kinematics of the synergistic 6 DOF motion

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*An actuator with a length of 1.0 m was used in the experiments described)

**Drifting of the actuator, due to its integration nature was countered by applying a manual offset.

system. The motion control then becomes a SISO position control system for each actuator, and is usually kept an analog circuit. The standard hydraulic servo concept is shown in Figure 8. Note that the feedback relies on the position signal q, and the acceleration-related signal $K_{\Delta P}$. No velocity signal is required. This technique cannot however compensate for interaction forces. It has also been shown that this concept is poor in robustness and has difficulty in compensating for variations in payload mass.

A more recent approach to servo control[16] is increasingly applied, especially in robotic control. In this concept, shown in Figure 9, the high-gain pressure feedback is used to achieve pressure tracking, while position tracking is obtained from the outer loop feedback. Load decoupling can be achieved through pressure feedback, while velocity signals are used for stability. In practice, there is an additional need for accurate velocity signals, accomplished by integrating the force (acceleration) signal.

The advantages to pressure control over position control are significant. Figure 10 shows a comparison of the closed loop frequency responses for the two systems, obtained from experimental analyses. The two columns show measured position and acceleration responses. Note the lower break frequency associated with the position feedback configuration (solid lines), and the larger phase difference. This is especially true in the acceleration signals, those most significant to simulator operations.

When the load is doubled (from 750 kg to 1500 kg), a similar phenomena is apparent, however the differences between the position and pressure-coupled systems are even greater (Figure 11).

Clearly, the pressure feedback configuration shows significant robustness in load variations as opposed to the position-controlled system. In the pressure feedback arrangement, the actuator behaves as a "force generator" via control by adequate feedback of differential pressure & velocity. Note that this robustness is due only to the control system configuration, while even further improvements could be achieved through the application of true robust control techniques.

These results suggest that the pressure feedback concept is also well suited to compensate for interaction forces, and can allow a flexible trade-off between position and pressure feedback control, since it represents an extension of the latter. It does however require computation of the velocity signal, and is sensitive to high-frequency dynamics of the moving payload. This last constraint stipulates high rigidity in the entire motion system, including the moving platform. In the next section, a novel and practical solution to light-weight, highly-rigid moving platforms will be presented.

High-Performance Motion Platforms

In order to maximize the motion performance of the entire simulator, it would be wrongful to disregard the natural properties of the motion platform, the payload-carrying element. A motion platform must sustain the occupants and equipment, and transfer the loads from the motion system actuators to the simulator cab. The occupants may include the pilot(s), instructors or experiment controller, and observers. The equipment payload will usually consist of the aircraft or aircraft-like instruments, displays, the controls and loading devices, electronic equipment required for the simulation, computer systems, and the visual display system. Modem simulators often employ wide-angle collimating display systems which use off-axis projectors mounted above the cab, presenting the image onto a spherical-section mirror, and via a rear projection screen. A result of this solution is a high contribution to the mass moment of inertia, while requiring a stiff mounting structure.

Traditionally, simulators are constructed in a layered fashion, beginning with a fairly rigid platform structure mounted atop the motion system gimbals. This platform supports then the cockpit replica with its interior, instruments, displays and controls. Behind the cockpit, an instructor cabin is placed where the instructor station and observers' chairs are mounted. Above this cabin, the display system projectors are mounted. The mirror structure is mounted directly to the platform at floor height.

The SIMONA Research Simulator (SRS), however, is not intended for training; therefore a number of the on-board systems can be simplified or neglected, reducing the total volume and payload mass requirements.

In efforts to reduce significantly the moment of inertia of the platform, a solution has been developed whereby the internal volume requirements are first defined, the constraints of the motion and visual display system established (so that no structure blocks the light beams or interferes with the motion system in any actuator position), and a structural shell placed around the occupants and internal equipment. An emphasis was placed on reducing the mass while maintaining sufficient stiffness of the entire system. Finite element analyses showed that a minimum natural frequency of 17.5 Hz could be achieved for the required configuration; a higher stiffness requiring increasingly more material, thereby raising the mass as well as cost. Lowering

the centre of gravity was also considered a crucial design objective. The result of the aforementioned exercise is a highly-rigid light-weight platform and a simulator which is capable of generating sharp accelerations. The resulting natural frequencies of the platform structural dynamics exceed those of the rigid and relevant aeroelastic aircraft dynamics. Furthermore, the small cockpit will place the pilot very close to the centroid of the upper gimbals of the motion system. In this way, maximum use of the pure pitch and roll capabilities of the motion system are provided to the pilot. It is also possible to create a large window free of reinforcing frames (Figure 12), while still meeting the aforementioned structural stiffness requirements. This allows a variety of cockpit interiors to be installed, and cosmetic window frames inserted if necessary.

The aramid/carbon fibre cockpit is equipped with carbon-fibre outrigger rods which accept the visual display system structure. A projector platform supports the CRT projectors, while a framework construction supports both the back projection screen and the mirror chamber. SIMONA is considering light-weight alternatives to the standard aluminized mylar mirror due to mirror resonance and mass concerns.

When complete, the cockpit of the SRS will allow fundamental research into human perception processes, interactions with displays, flight control concepts, and flight dynamics models. Note that with the high performance expected in this motion system, the human perception systems will not be polluted parasitic errors, thereby yielding new opportunities for future work in this area.

The SRS integrated system is shown in Figure 13. The development of this simulator, a major technical challenge, has in itself been an exercise in applying all facets of simulator technology, combined with new applications of materials, control theories and design integration.

Conclusions

Achieving high-fidelity motion cues in flight simulators involves re-addressing all major areas of both the hardware and the control system. The approach described in this paper will lead to significant improvements in motion cue capabilities, especially in the high-frequency regimes. Pressure-based control systems can compensate for load variations and, later, robust control applied to the actuators can overcome internal system variations. The multivariable six-degrees-of-freedom control system will ensure that the actuator controllers are fed with signals taking into account predictions of the system state. Moreover, the SRS platform design philosophy suggests that the total motion system performance can be increased through the use of high-stiffness light-weight materials.

Research in the SIMONA programme will continue to refine these areas, and also consider new approaches to motion washout.

Acknowledgments

The Netherlands Ministry of Education, Science and Culture, and the SIMONA Industrial and Scientific Partners are thanked for their financial support of the SIMONA programme. The authors would also like to thank ir. G. van Schothorst and ir P.C. Teerhuis (Faculty of Mechanical & Marine Engineering) for their contribution to this paper.

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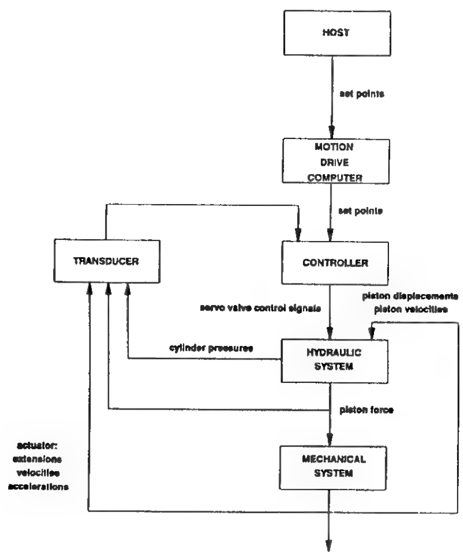

Figure 1. Simulation Model Structure [8]

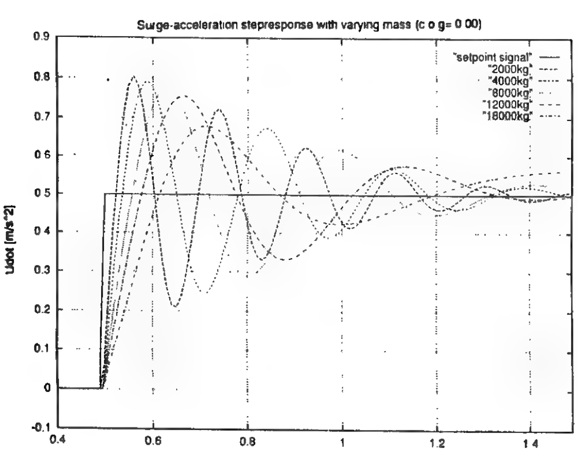

Figure 2. Motion System Response in Surge Acceleration, Variations in Platform Mass Shown [9]

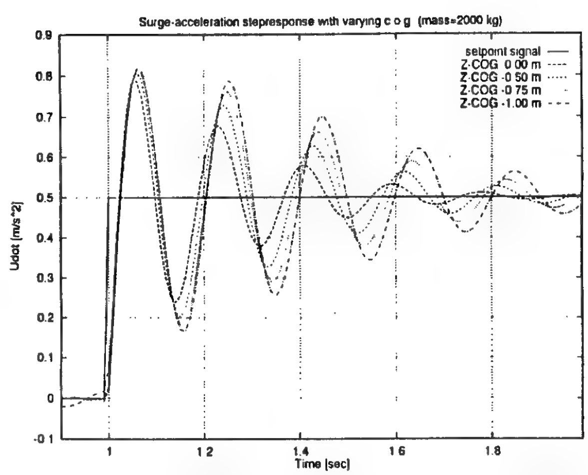

Figure 3. Motion System Response in Surge Acceleration, Variations in Platform Centre of Gravity Vertical Offset Shown [9]

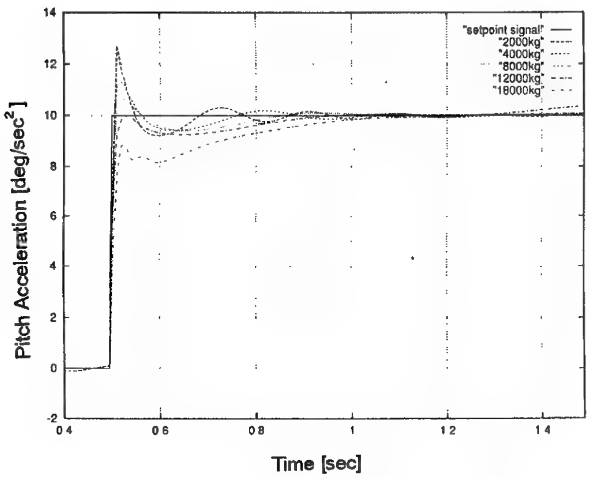

Figure 4. Motion System Response in Pitch Acceleration, Variations in Platform Mass Shown [6]

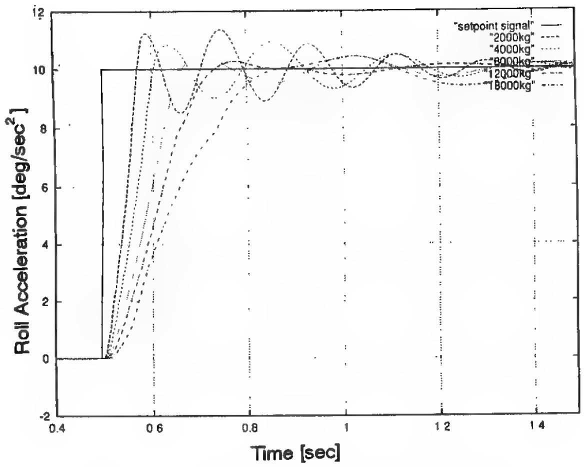

Figure 5. Motion System Response in Roll Acceleration, Variations in Platform Mass Shown [6]

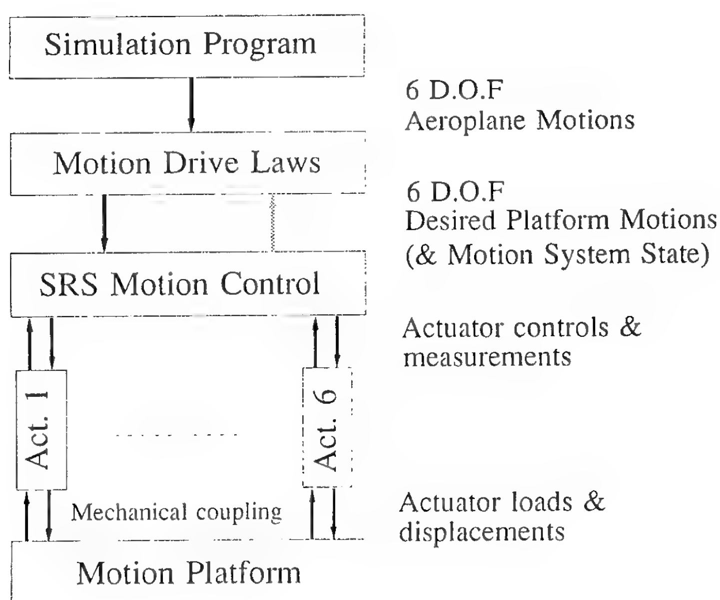

Figure 6. SIMONA Motion System Control Concept [15]

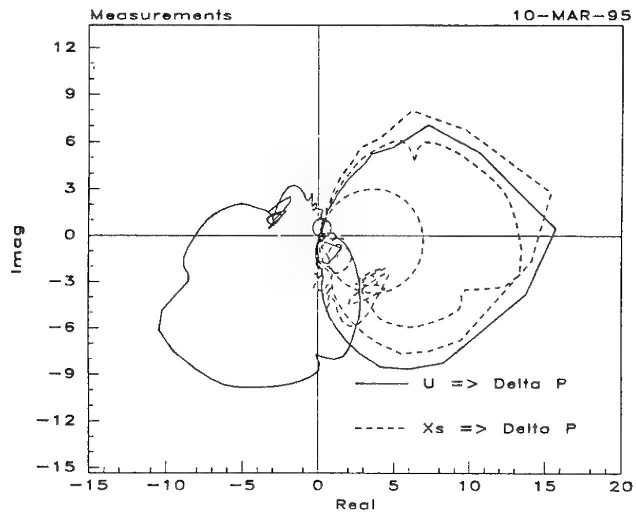

Figure 7. Nyquist Plot of Open-Loop Control Gain, with and without Valve Dynamics [15]

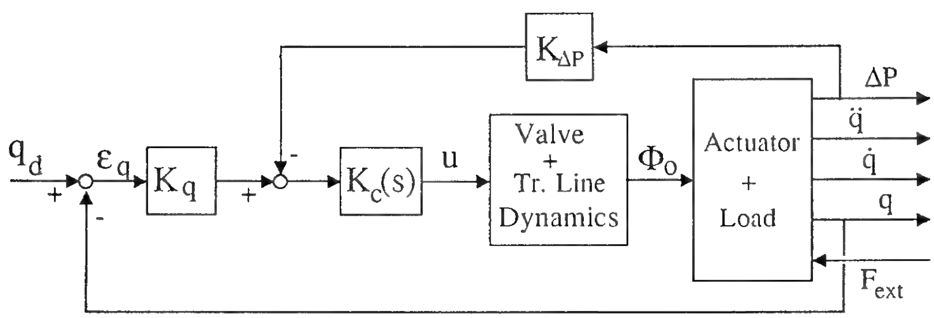

Figure 8. Position-Based Servo Control Concept [15]

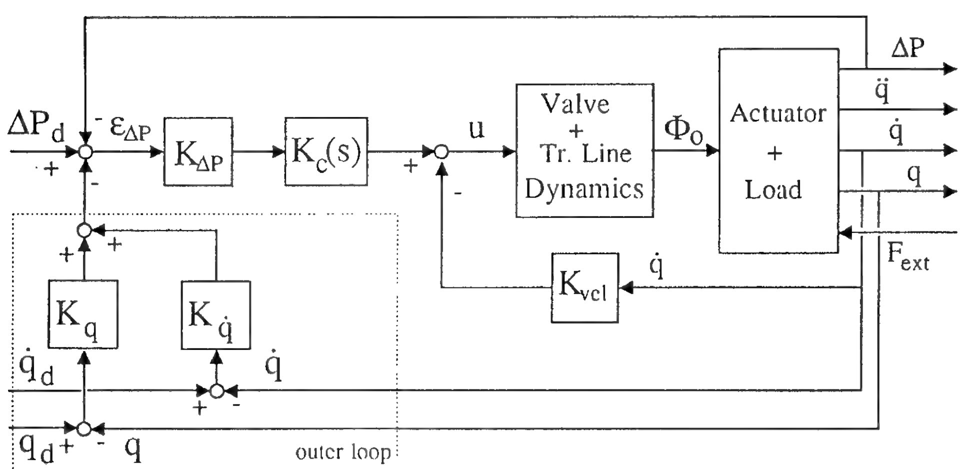

Figure 9. Pressure-Based Servo Control Concept [15]

$$\frac{q(s)}{q_d(s)} \qquad \frac{\ddot{q}(s)}{\ddot{q}_d(s)}$$

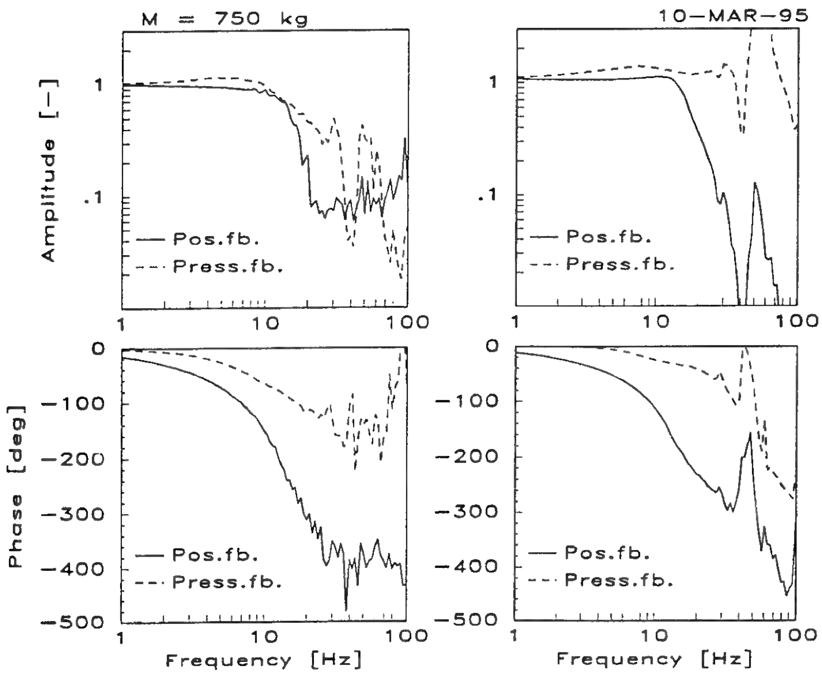

Figure 10. Comparison of Position and Pressure-Based Actuator Control; M=750 kg [15]

$$\frac{q(s)}{q_d(s)} \qquad \frac{\ddot{q}(s)}{\ddot{q}_d(s)}$$

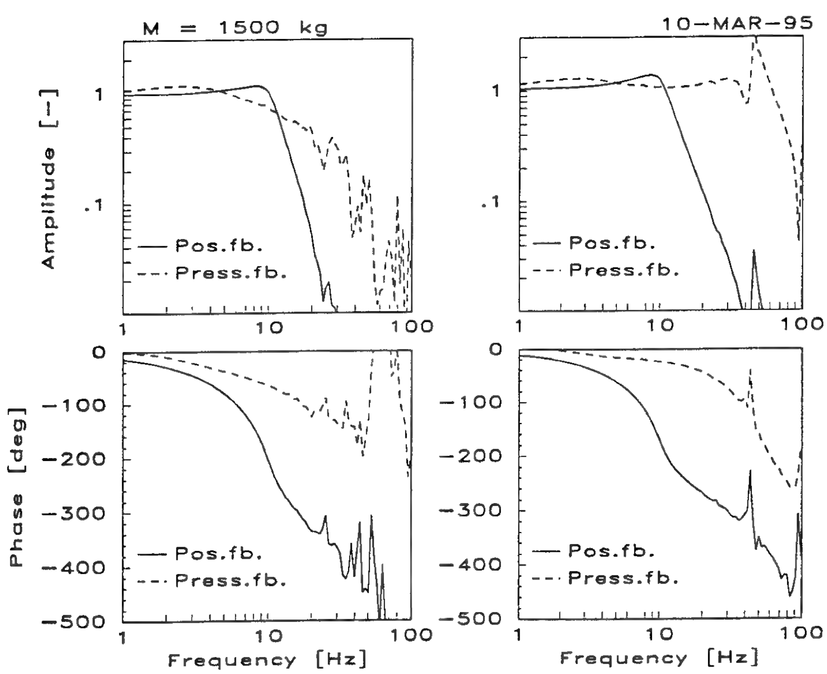

Figure 11. Comparison of Position and Pressure-Based Actuator Control; M=1500 kg [15]

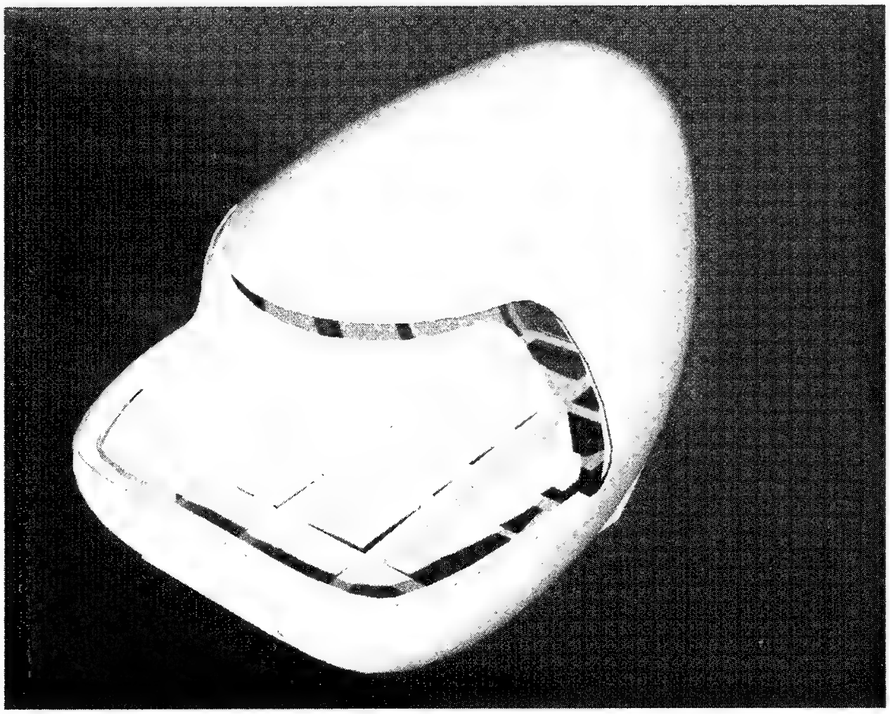

Figure 12. Composite Materials Motion Platform/Flight-Deck of SIMONA Research Simulator

Figure 13. Integration of SIMONA Research Simulator

APOGÉE : A BREAKTHROUGH IN SYNTHETIC IMAGE GENERATION

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SUMMARY

Though polygon and pixel capacity remain significant parameters of real time image generators, the visual aspect and the content's quality of the images take more and more importance with their utilization in NOE flight of helicopters, or combined arms simulation and interoperability context. In this field, APOGÉE represents a breakthrough in real time image quality and complex scene content restitution.

An improved management of the database guarantees the best restitution of the scene content accounting for the specific polygon and pixel capacity of one system.

AZtec*, the new algorithm developed by Sogitec for hidden part elimination and antialiasing, allows for processing of opaque, transparent, or lighting polygon participation, in any number and in any order. A nice rendering of complex scenes, regarding the lighting and shading aspect, is obtained without the sorting constraints encountered in similar systems, to process transparent faces at the end of the computation cycle.

On the whole, the optimization and the integration of all stages of the APOGÉE image computer, provide the best figures on all image generation criteria, and offer modularity in terms of performance and image definition.

RÉSUMÉ

Bien que les performances en polygones et en pixels demeurent des paramètres significatifs des générateurs d'images temps réel, la qualité du contenu des images prend une importance croissante avec leur utilisation en simulation de vol tactique d'hélicoptère, ou d'opérations interarmes. Dans ce domaine, APOGÉE représente une percée dans la génération d'images de qualité et la restitution de scènes complexes.

Une gestion optimisée de la base de données assure la meilleure restitution du contenu de scène, compte tenu des capacités particulières d'un système.

AZtec*, le nouvel algorithme développé par Sogitec pour le traitement de l'aliasing et des parties cachées, permet la restitution de surfaces opaques, transparentes ou éclairantes, en nombre et en ordre quelconques. Un rendu réaliste, particulièrement au niveau de l'éclairement et de l'ombrage, est obtenu sans les tris obligatoires, dans les systèmes similaires, pour traiter les parties transparentes en fin de cycle.

L'intégration et l'optimisation à tous les étages du calculateur d'images APOGÉE procurent les meilleures caractéristiques pour tous les critères de la génération d'images, avec une grande modularité en performance et en définition d'image.

1. INTRODUCTION

The simulation domain generates severe constraints for the design of real time Image Generation systems:

- Time constraint: In man in the loop simulation, the lowest transport delay is required, with update rates of 60 Hz, or higher. A dedicated architecture must be designed to satisfy this major requirement.

- Database Coverage: Today's mission training requires to fly over huge territories, exceeding one million square kilometer. This implies an efficient database organization and management accounting for geographic coordinates..

- Scene Content: Very detailed scenes must be represented to simulate complex combined operations, and when no explicit data is available in the database, artificial features must be generated to maintain movement and position cues.

- Image Quality: To obtain the best training efficiency, the synthetic nature of the images should be forgotten by the trainees. The scene representation must be realistic, without distracting effects which degrade the training effectiveness.

The way these constraints have been dealt with in APOGÉE are described in the followings.

2. ARCHITECTURE

Most of the Image Computer performance is directly related to the architecture and the way the different computations are sequenced. The APOGÉE system is composed of two sub-systems:

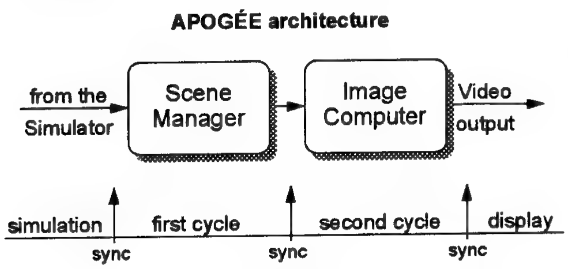
- the Scene Manager, a VME-based computer witha real-time operating system,

- the Image Computer, a dedicated architecture developed by Sogitec, with proprietary busses.

* AZtec: *Advanced Z-buffer technology. Sogitec proprietary algorithm.*

Paper presented at the AGARD FVP Symposium on "Flight Simulation — Where are the Challenges?", held in Braunschweig, Germany, from 22-25 May 1995, and published in CP-577.

Both are synchronized on the video rate. Each of them takes one frame cycle to perform its tasks.



An image is then displayed two cycles after new position parameters transmitted by the simulation host computer.

2.1 The Scene Manager

The Scene Manager performs several tasks among them are the interface with the simulation host computer, the management of the database, the control of the image computer, and other simulation support functions.

- Interface: The Scene Manager ensures the interface with the simulation host computer, the transformation of simulation data into image parameters (ownship and moving models position and attitude, weather effects, time of day control, special effects, etc.), and the control of the image computer. The Scene Manager sends back IG and scene status to the simulator.

- Database management: The Scene Manager supports the storage of the visual database and geospecific phototexture patterns, as well as auxiliary databases. At the mission initialization, the necessary part of the database is loaded in the Image Computer. A real time paging of the terrain database is then performed accounting for the movement of the ownship.

- Mission support functions: Though not really in the concern of the image generation, the Scene Manager performs several mission support functions such as height above terrain determination, terrain following for terrestrial objects, collision detection for the ownship and the moving models, multiple point range finding and intervisibility. Using auxiliary databases, the Scene Manager benefits from the knowledge of the scene context and terrain characteristics.

2.2 The Image Computer

The Image Computer is composed of four processors. the Extraction processor, the Geometry processor, the Pixel processor and the Video processor.

An image is computed in one frame period, based on parameters transmitted in the previous cycle, and it is displayed in following period. Three processors (the Extraction processor, the Geometry processor and the Pixel processor) participate in the computation of one image, while the previous image is displayed by the Video processor.

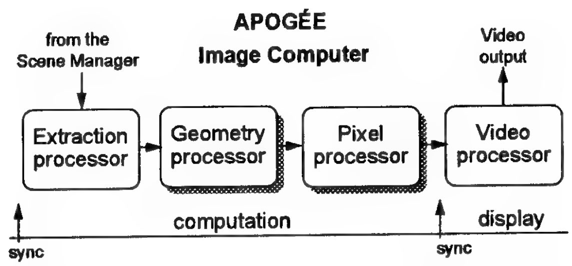
The Extraction Processor and the Geometry Processor are based on the same computer unit (CGP board).

- The Extraction Processor is composed of one CGP board equipped with additional memory which supports the local database.

- The Geometry Processor is a parallel structure of up to eight CGP boards. Due to the high throughput of the polygon bus and the protocol used, there is no derating on computation power with the number of boards.

- The Pixel processor is a parallel pool of up to eight dedicated CIP boards. One board is composed of four pixel processor cells in parallel, and contains twenty ASIC of four different types.

- The Video Processor is dedicated to convert the content of the image memory into video signals. It is also used to process the image for edge matching in multichannel projection, to generate operational symbology, and to manage calligraphic lightpoints, if any.



The design of these processors provides the better performance, and the derating in the pixel processing capacity versus polygon count which is usually encountered on such systems is therefore suppressed.

3. DATABASE

Large territory coverage requires an optimization of the database storage and access, along with a real-time paging process.

3.1 Terrain database

The terrain is described as a Triangle Irregular Network (TIN) with vertices coordinates and associated attributes The TIN is preferred to the regular mesh which, due to the uniform density of polygons, generates a higher mean-error of position and altitude for the same volume of data, and can only provide a coarse representation of the relief.. For load control purpose, the database is stored under several Levels Of Detail (LOD) descriptions.

The terrain is textured using satellite photographs. Fine levels of detail will preferably be covered with aerial photography, giving a lower step per texel. Texture pattern are stored in the image processor and a real-time paging of texture is performed accounting for the movement of the ownship, in the same way as for terrain geometry.

3.2 Object database

Objects are not explicitly described in the terrain database. Only their identifier and position, as well as some layout parameters, are stored in this database. Furthermore, the object database volume is greatly reduced in so far as each object instance costs only few words instead of the full object description.

This gives a local database capacity of up to 650 000 terrain polygons and 350 000 object instances, that are stored in the Extraction processor memory.

For the real-time object's instanciation, an object library is available in the Extraction processor. This allows rapid and easy database creation and modification, particularly regarding the object density. For operational purposes, objects can be put on the terrain at the time of the simulation initialization.

3.3 Objects library

The explicit description of objects is done in the object library. Eight LOD per object can be created, and stored in this library. Up to 4096 classes of objects are managed, with their levels of detail and an alternate representation, for object's destruction purpose.

Objects Library

4. SCENE CONTENT

If a perfect rendering quality provides a visual comfort, the way the content of the scene and the interest of features are managed provides the "intelligence" of the image.
All is done in APOGÉE to control the operational quality of the scene content.

4.1 Level of Detail Management

According to the distance from which the features are observed, their description can greatly differ. This is used to define levels of detail for terrain and for objects, in order to optimize the polygon capacity of the image computer.

The choice of a level of detail representation is done, for all features, according to their visual aperture and operational parameters.

For each object, the appropriate LOD is selected accounting for the field of view, the distance to the observer, the angular offset in the field of view (for wide field of view configuration with AOI), and some criteria like operational interest (an ordinary tree or house will be sacrificed earlier than a designated target).

Objects pop-up is avoided using size and transparency blending. A blending between two intermediate LODs can also be done, but is time consuming. In fact, the best result is obtained modeling each object LOD in such a way that, in nominal conditions, the detail modification is unperceptive at the transition.

4.2 Terrain interpolation

The terrain database is stored by rectangular block entities. Depending on their range to the observer, and operational considerations, each block of database is extracted with the optimum LOD.

In order to avoid abrupt transitions between successive LOD representations, a couple of coordinates is associated to each vertex in one level of detail description: the actual coordinate in the current LOD, and the corresponding coordinate of the same vertex in the following LOD.

An interpolation is then computed on the coordinates of vertices located between two higher and lower range limits around the LOD transition range. The transition between the different representations is then smooth, and unperceptive in the nominal condition.

4.3 Animation

Independently of moving models, which are controlled from the host computer with six to nine degrees of freedom, objects in the database can be endowed with individual dynamic characteristics.

- **Self Animated Models**: Each object in the database can be composed of several parts, some of them being fixed, others being animated along predefined degrees of freedom. This allows the animation of some objects (radar antenna, or windmill for example) without any requirement to the host computer or to the scene manager.

- **Multiple Representation Objects**: Some objects can be modeled with up to 256 representations. Two kinds of animation are possible using this capability: automatic cycling on the different representations, or sequential selection, on scene manager initiative, in a predefined list of representations (scenario). Troop maneuvers, or dynamic object's destruction, for example, can be simulated in this way.

5. POLYGON PROCESSING

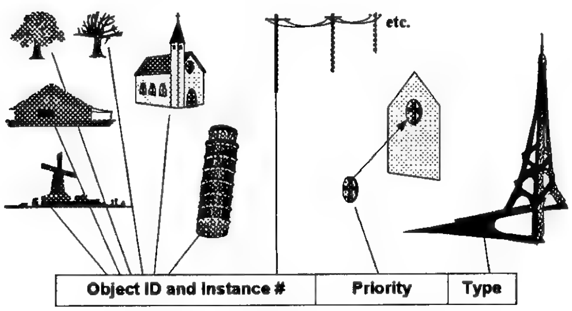
From the database to the input of the pixel processor, the image generation is based on a polygonal description issued from the Extraction processor, then

transformed in the Geometry processor.. Light points are computed in the same way.

5.1 Extraction

Depending on the view point and the field of view, the visible blocks of terrain description, and object's instances, are extracted from the local database accounting for the above mentioned LOD criteria. Selected terrain features and objects are extracted in the direct visibility order to optimize the Pixel processor efficiency.

The heritage of polygons is associated to the descriptors using a tag in which several fields corresponding to the origin of polygons (terrain/object, object type, and specific properties) are concatenated with the object number. This tag will be used later on in the pixel processor to help the AZtec process.



Tag generation

At the output of the extraction process, packets of vertices, gathered per object or terrain block, are then transmitted to the geometry processor.

5.2 Geometry processing

One of the available CGP boards handles one packet at a time, and performs the usual 3D geometry computations - Change of coordinates, Clipping (if any), Perspective projection - on each vertex. In the same time, the luminance is computed accounting for the normal vector and the light sources parameters.

Vertices parameters are then known in the projection (post-perspective) space. The polygon descriptors are composed in a format dedicated to the rendering by the pixel processor, the pixel attributes (color, luminance, etc.) being described by the coefficients of their equation in the projection plane.

In the pixel processor, the attributes per pixel will be obtained applying the coordinates (X,Y) of each pixel in the parameter equations. This eliminates the usual computation errors due to the bi-linear interpolation of the parameters in the polygon.

The equation coefficients of polygon edges are transmitted, associated to the polygon descriptor, along with bounding box parameters. This bounding box will be used, in the the pixel processor, to speed up the impact function and the segmentation process which determines the useful part of the screen covered by each polygon.

5.3 Light points

For night scene, or landing aid simulation, for example, the geometry processor generates lightpoint descriptors that are transmitted to the Pixel processor.

Two kinds of lightpoints are generated by APOGÉE:

- **Raster lightpoints**, that are processed in the same way as the polygons. Their intensity is computed accounting for the distance to the observer and a specific attenuation table. In the pixel processor, they are rendered as textured polygons the size of which is growing with the intensity in order to compensate for the lack of video intensity range.

- **Calligraphic lightpoints**, that are processed in the same way, down to the occultation stage where they are only checked for occultation, without modifying the image content.

In both cases, lightpoints can be omnidirectional or not. They can have colored lobes to simulate some landing aids like VASI.

6. PIXEL PROCESSING

The Pixel processor generates color attributes per pixel, and resolves the occultation between polygons.

The pixel processor consists in three main stages: the Segmentation processor, the Rendering processor and the Occultation processor. A parallel architecture has been designed with two objectives: modularity in term of image resolution and in term of image complexity and quality.

The pixel processing is then done by screen zones of 64 x 64 pixels. The number of installed CIP boards is variable depending of the update rate, the image resolution and pixel processing requirements.Up to eight CIP can be combined.

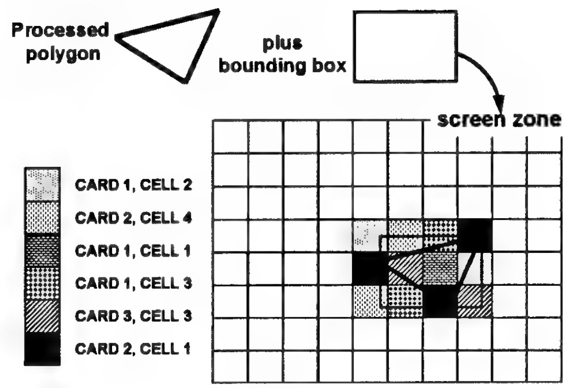
Each CIP board is composed of four identical processing cells. Depending on the image definition and the level of performance, a processing cell will have a variable number of screen zones to process, with a maximum of 32 zones per cell. Moreover, each 64 x 64 zone can be processed by several cells in order to average the computation load.

6.1 Segmentation Process

The first step of the pixel process is to determine which pixels in the screen belong to the polygon. This is done by the impact and the segmentation functions.

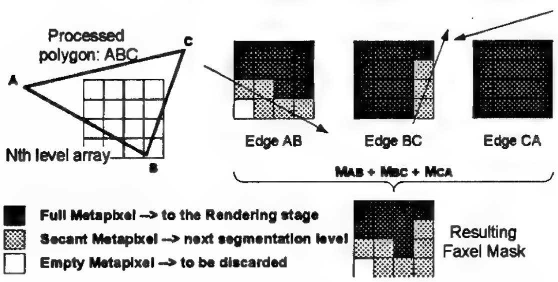
- **Impact**: The impact function is located on each CIP board. Using the bounding box parameters, it determines which CIP board(s), and which processing cell(s) in a board, has to deal with each polygon descriptor. An impact table is adapted to a Pixel processor configuration and an image resolution.

Several CIP boards can process the same polygon, and on each CIP, four cells can work on the same polygon, depending on its trace on the screen space.



Screen Impact function

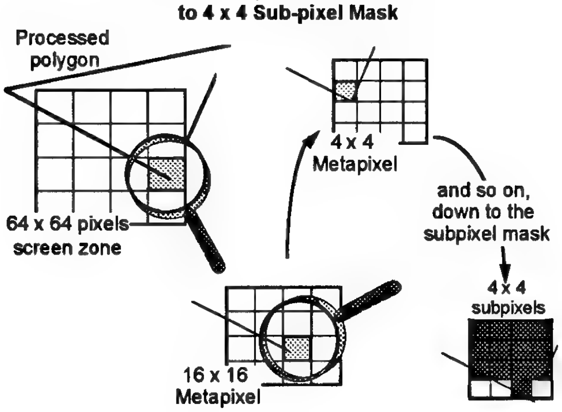
- **Segmentation**: All the cells concerned by one polygon perform a recursive segmentation of this polygon into metapixels (blocks of 16x16, 8x8 pixels, etc.), down to the sub-pixel mask per fragment of polygon in a pixel. In the followings, the polygonal participation to one pixel will be called "Faxel".



Edge by edge Segmentation process

The polygon segmentation is done, edge after edge, using the edge equations. Full metapixels are directly transmitted to the rendering stage, while edge metapixels are segmented again to generate lower size full metapixels or edge metapixels or, at the last step, faxel masks of 4 x 4 sub-pixels.

Hierarchical Segmentation from 64 x 64 pixels Screen-Zone to 4 x 4 Sub-pixel Mask



The sub-pixel mask participation is based on its center position relatively to the polygon edges, and is corrected accounting for the area covered by the faxel.

- **Meta-Zbuffer**: During the segmentation process, hidden metapixels are eliminated from the dataflow by using a Z-buffer function at the meta-pixel level. This will be detailled later in the occultation paragraph.

6.2 Rendering

The rendering process is devoted to the computation of the color components of the faxels. Two main types of rendering are processed: color and luminance smoothshading (Gouraud shading), and texturation with luminance shading.

- **Smooth shading**: Four component equations are processed (L, R, G, B), in which the X,Y coordinates of the faxel sampling points are applied.

A scene attenuation factor is transmitted apart in floating format, the color components being computed at the maximum level of illumination.

This attenuation factor is used in the last stage of the pixel process, and permits the correct rendering of night/dusk scenes with light lobes illumination.

- **Texturation**: Full color photographic texture can be applied on all polygons.

Patterns can be used with up to 1024 x 1024 texels definition. As they are processed in normalized coordinates, texture patterns can be laid out regardless their original definition.

Texture patterns are described in full color mode (R, G, B) plus transparency, and a global transparency factor can be applied on a textured polygon. Modulation patterns can also be applied. Photographic texture is processed using the MIP-map algorithm.

In the texturation process, three component equations (L, Tx, Ty) are computed. The L parameter is used for the smooth shading. Texture coordinates (Tx, Ty) permit to obtain, after inverse perspective computation, the coordinates of the processed faxel in the original texture space. The texture number is then concatenated to these coordinates to address the texture memory of which the color components R, G, B and a transparency parameter are extracted.

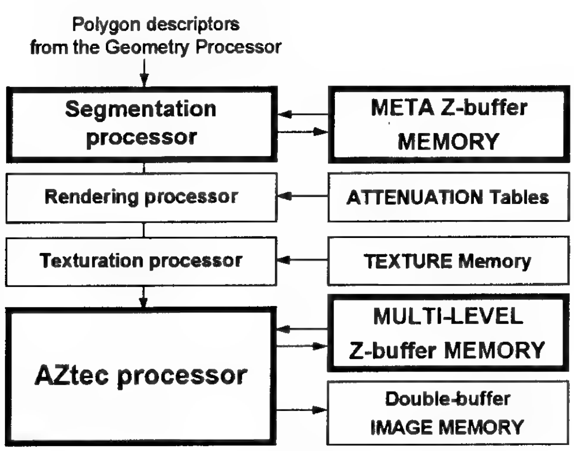
- **MIP-map**: Texture being rendered with MIP-map, the texture pattern are stored under several decreasing resolution maps obtained by successive lowpass filtering. A gradient of texture address is computed per pixel, in order to determine which optimum texture couple of maps must be addressed. The fractional part of this gradient is used to interpolate between the two selected maps. This interpolation avoids the visible transition band when only one level is used at a time. A better rendering is obtained with a bi-linear interpolation in each map, using the fractional part of the texture addresses, before interpolating between the two selected maps.

- Sharpening: When the higher resolution map is used, and the texture map is largely oversampled, the image has a blur aspect. A sharpening function is then engaged to render the boundaries of the texels, in order to restore attitude and movement cues. The sharpening level is a programmable parameter.

- Microtexture: The above conditions can be easily obtained when flying nap of the earth, or running on the ground. Along with sharpening, better cues are obtained by adding higher detailed microtexture. The microtexture is a generic pattern, matched with the original ground pattern, which gives a gain in the range of texture use. The 10 MIP-map levels can then be virtually extended to 15 or 20 levels.

6.3 Occultation

A major problem in the Computer Image Generation is the hidden parts elimination. The well-known Z-buffer algorithm, largely used in most image generators, has been criticized for its inherent difficulty to perform antialiasing, and its sensitivity to depth complexity. Two functions have been implemented in APOGÉE: a Meta-Zbuffer at the Segmentation level, and AZtec, a Sogitec proprietary algorithm.



Meta Z-buffer

6.3.1 Meta-Zbuffer

The efficiency of the Z-buffer is improved using a Meta-Zbuffer algorithm in the image processor.

The Meta-Zbuffer consists in the management of an early Z-buffer in the Segmentation process. It starts at the 16 x 16 metapixel level. The Meta-Zbuffer runs similarly to the Newell algorithm, and it is maintained in the different stages of the segmentation process, down to the pixel level: During the segmentation steps, all metapixels that are farther than previously stored metapixels are rejected from the data stream.

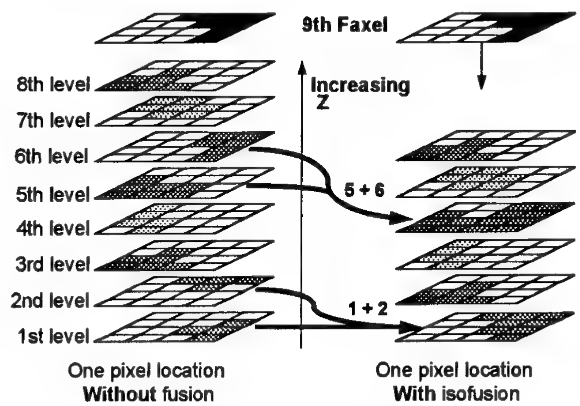
The Meta-Zbuffer function is all the more efficient that polygons are presented to the segmentation process in the visibility order. This is guaranteed by the extraction processor where features are sorted.

This sort is not a heavy constraint in so far as it is limited to objects, and not polygons. The AZtec pixel processing load is thus greatly reduced. This improvement is particularly appreciated in sensor configurations with narrow field of view, where very high depth complexity can be encountered when several objects intersect the line of sight, and occupy most of the screen area.

6.3.21 AZtec

AZtec is the most significant improvement in image generation. Derived from the well-known Z-buffer algorithm, with A-buffer improvements, AZtec can be qualified as a "multiple Z-buffer with adaptive blending". Based on the management of several layers of 4x4 sub-pixel mask, area and color parameters per pixel, it takes advantage of the tag generated at the Extraction.

AZtec technology is not only a solution to the occultation problem, but it participates to the final rendering of the image, particularly in the lighting and shadowing effects, and allows for nice rendering of any number of opaque, transparent, or lighting polygon participations, in any order.



Multilevel Z-buffer

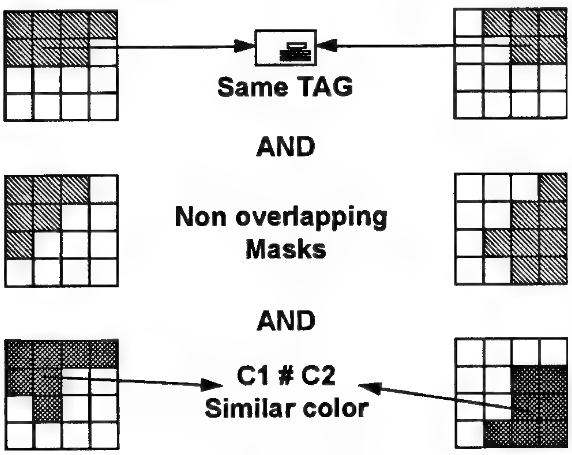
In fact, AZtec runs with a eight level stack of faxels, regardless their processing order or whether they are opaque, transparent, shadows or lighting part of polygons.

Obviously, all faxels that are hidden by a full opaque faxel (16 opaque sub-pixels) are eliminated, in the same manner as with ordinary Z-buffer. Only faxels that have at least one visible sub-pixel (opaque or transparent) remain active in the stack.

Complex situations with a concentration of details plus two or three transparent layers for atmospheric effect or special effects could lead to an overload of the eight levels stack. To avoid such cases of overload, a fusion process has been implemented in which two levels can be merged into a single level.

Three types of fusion are performed in AZtec: Isofusion Multitexture fusion, and Forced fusion.

- **Isofusion**: In this case, two faxels are merged into a single faxel accounting for several conditions:
  . The two faxels must have the same TAG
  . They must have non overlapping part
  . The color distance between the two faxels must be lower than a predefined threshold

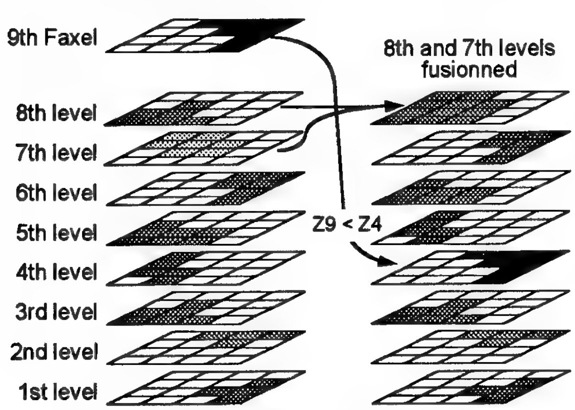


Isofusion criteria

The isofusion helps to maintain the stack under the maximum number of levels without any compromise on the image quality. The last condition ensures that two faxels with contrasted colors are not simply merged, though belonging to the same object, in which case a color error could occur if one of the two faxels had to be hidden later.

- **Multitexture fusion**: This is a particular case of isofusion where the two masks may overlap. Color are blended in the ratio assigned to each texture. Any number of textures can be applied to one polygon, the result taking only one level in the stack.

- **Forced-fusion**: When none of the above mentioned fusion process can be applied, the incoming faxel is stored in the a new stack level. One must remark that transparent faces occupy one level each as long as the image computation is not complete.



Forced fusion

If the stack is full when a faxel has to be processed with no isofusion capability, Forced fusion is performed. Accounting for the depth test and occultation process, the incoming faxel may be discarded or inserted in the stack, in which case the 7th and the 8th faxels in the Z-hierarchy are considered. One of these two faxels is discarded, or merged with the other, depending on whether they are opaque or transparents. In all cases, the best compromise is adopted.

Forced fusion is a remedy to deal with extremely complicated situations, with a conglomeration of objects the edges of which interfere in a pixel. Generally, this occurs far from the observer, and the approximation on the final color has no significant effect in the result. The main problem is to avoid brute rejection of faxels. The forced fusion is efficient in local, and not much likely to occur, accumulation of transparent faces. In this case, transparent polygons are generally overriding the rest of the polygons, and therefore are not affected by forced fusion.

6.3.3 Lighting

In the final step of the AZtec process, the content of the multilevel Z-buffer memory is converted into color components accounting for the optical path. The 4x4 sub-pixel masks are combined with their opaque or transparent attributes.

At this level, true lighting conditions are computed. The rendering of shadows, or the lighting due to headlights, landing lights or searchlights, are applied to the faxels hit by the light sources. The color of faxels is computed in full daylight condition throughout the rendering pipeline. Dusk or night attenuation is applied at the last stage of AZtec, and modified with the lighting faxels, the intensity of which have been determined using the true 3D distance and a dedicated attenuation table.

Several chromatic sources can be processed. Their illumination is added, per color component, on the pixel basis; giving the capability to restitute colored light effects according to the color of the features (only red and green objects will be highlighted by a yellow light, for example).

The final color components are stored in a double buffer image memory.

7. VIDEO PROCESSING

7.1 Video output

The basic function of the Video processor is to convert the content of the image memory into analogic video signals, according to the selected video standard. The image memory content is generally not used straight out. Some operations can be done on the raw image.

A contour mask can be applied in order to facilitate multichannel projection integration. In the same time,

a color selective attenuation can be applied for multi-channel projector/screen harmonization. The color components are finally modified using a look-up table for compensating variable display Gamut.

7.2 Symbology

Symbology is often useful in some simulation applications. It is mainly composed of various text and vectors, together with application specific symbols. This symbology is generated by the video processor, and inserted in the video signal under fifteen programmable colors.

7.3 Calligraphic light points

Calligraphic lightpoints are not displayed in the standard video signal. The occultation status of the calligraphic lightpoints is read in the multilevel Z-buffer memory by the Video processor in order to display only the visible lightpoints. A dedicated interface board is added to the Video processor to transmit the lightpoint data according to the different multimode (raster/calligraphic) projectors.

7.4 Sensor Simulation Aid

The image reading capability is used in the simulation of thermal imagery systems (detection and tracking of contrasted area). As the pixel history remains available in the multilevel Z-buffer memory at the end of the image computation, it is used in the simulation of some systems (multiple echo laser range finding).

Their efficiency through haze, clouds, or some partially transparent objects, though targets are not visible in the final image, can be simulated. Double echo laser range finder can thus be simulated.

8. CONCLUSION

Optimization have been done, at all stages of the APOGÉE image generator, which provide the best performance on all Image Generation criteria, and in a broad range of applications. An efficient scene management, together with improved rendering algorithms, participate in the generation of realistic images, with a great content complexity and a high level of quality.

While most of the deficiencies of the original Z-buffer algorithm have been definitely suppressed, appropriate trade-off have been made to allow hardware implementation of a A-buffer like algorithm, improving performance together with image quality.

Significant breakthroughs in real time image generation have been made by introducing new features such as multiple, true pixel range, colored light lobes and multiple transparency, without adding sorting constraints as encountered in other systems.

The final product offers modularity in terms of performance and image quality. Only four types of boards are used for all configurations, providing a great simplicity of maintenance, very few spare boards and therefore, a low life cycle cost.

The RTSS Image Generation System

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1. SUMMARY

Main market demands for the visual system of a simulator are photorealism and low latency time. RTSS, a general purpose image generation module developed within the European ESPRIT project HAMLET, can meet these demands through the use of High Performance Computing technology. This technology provides the needed communication and computing power. Moreover, by using parallel processing, the whole system is scalable, i.e., the same software and hardware design can be used for small, cheap systems, as well as for high-end view simulations. This allows an easy adaptation to the user's needs.

RTSS also includes an object and scenario editor implemented on a work station, as well as filters to other object data standards.

This paper will give an introduction to the soft- and hardware design of RTSS. It will then present the features of the system as well as the interfaces: the filters to import external model data and the interfaces to the simulation system itself.

2. RTSS

2.1 Overview

Within the context of the European ESPRIT Project 6290 HAMLET, TNO Physics and Electronics Laboratory (TNO-FEL, NL), Deutsche Forschungsanstalt für Luft- und Raumfahrt (DLR, D), and Constructiones Aeronauticas (CASA, E) developed the Real-Time Simulation System (RTSS).

The work in the HAMLET project is done within the framework of the ESPRIT program and partly funded by the Commission of the European Communities. The following companies form the HAMLET consortium: AEG (D), CAP Gemini (F), CASA (E), DLR (D), HITEC (GR), INESC (P), INMOS (GB), Parsytec (D), Gabriel (GR), TNO (NL), and TU Munich (D).

The RTSS is a general purpose image generation module. RTSS can be used by simulators, e.g., flight simulators (see Fig. 1), and other man-in-the-loop applications which require visual feedback.

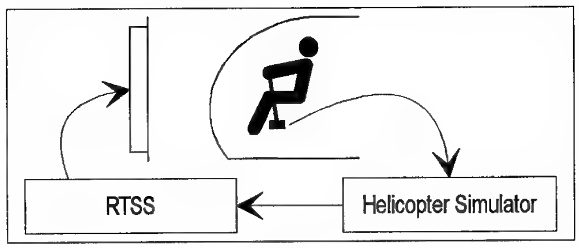

Figure 1: The RTSS Concept

RTSS has to generate photo-realistic images in real-time. To realize this, the underlying hardware has to provide a high computation power. Moreover, the data bandwidth needed to communicate the large data flows processed by the RTSS places severe demands on the communication power of the underlying hardware.

RTSS is designed to be scalable. If the demands of an application are rather low, a small (and, therefore, cheaper) system can be used. If the demands get higher, the RTSS can be expanded to fulfil the growing requirements. Requirements are the image rate and the latency time, as well as features like shadow generation, anti-aliasing, and the size of the database.

RTSS is divided into an off-line and an on-line part. The off-line part consists of an interactive object and scenario editor and filters to input data from known geometric formats such as the MultiGen Flight format. The objects and scenarios are stored in a database in a file system.

The on-line part inputs this database, i.e., data describing the geometry and appearance of objects, light parameters, image parameters, etc. RTSS then outputs the corresponding image. As a second task, RTSS contains a collision detection module. This module checks the moving objects for collisions and reports them back to the application. During run-time, the application can change almost all parameters, e.g., the position and orientation of all objects and of the camera, light positions and parameters, etc.

The interface to the application is a bi-directional channel. The application sends commands (parameters, movement data, object changes, etc.) to the RTSS and receives in turn the results of the collision detection.

Paper presented at the AGARD FVP Symposium on "Flight Simulation — Where are the Challenges?", held in Braunschweig, Germany, from 22-25 May 1995, and published in CP-577.

2.2 Requirements and Architecture

Using RTSS in man-in-the-loop applications leads to the following main requirements

- real-time generation of images,
- an ergonomic image rate,
- a low latency time, and
- high resolution, photo-realistic images.

Since no restrictions in the movement of objects are acceptable, the images cannot be pre-calculated but must be calculated in real-time. To guarantee a smooth movement of objects in the image, the image rate must be about 20–30 images per second (depending on the dynamics of the application). A low latency time is dictated when RTSS is used in man-in-the-loop applications. The time between the command of a user in the application and the display of the corresponding image, i.e., the latency time, should be below 100 milliseconds to prevent motion sickness or severe timing differences between the simulator and the real thing. The image must be realistic enough to serve as a visual orientation. It should contain shadows as a visual clue for the position of objects, a high resolution, and anti-aliasing techniques should be used to suppress edged lines and edged object boundaries.

The above requirements led to the following specifications of the RTSS. For the off-line definition and construction of objects, RTSS provides:

- an interactive, three dimensional scenario and object editor;
- import of external model data (MultiGen, AutoCAD, etc.);
- static and dynamic objects with several levels of detail;
- hierarchic grouping of objects;
- objects are built up from points, lines, and planar polygons;
- polygons can be textured;
- multiple dynamic directional light sources.

During run time RTSS reports:

- collisions between objects on polygon level.

The following features are used for the resulting image:

- light reflection and emission using multiple light sources and several lighting models;
- shadow generation;
- anti-aliasing and depth cueing (fog simulation).

The performance specifications are:

- true colour (i.e., 24bit) images at high resolutions;
- 25 images per second;
- a latency time of 80 milliseconds.

2.3 Architecture

RTSS is decomposed into three subsystems, corresponding roughly to the three companies involved in its development: the Scenario Creation (CASA), the Simulation Execution (DLR), and the Image Generation (TNO) subsystem (see Fig. 2.)

The Scenario Creation subsystem (see chapter 3) is the off-line part of the RTSS and includes the scenario editor, the object editor, and the external model data import module. The resulting scenarios are stored in files to be loaded by the on-line part of the RTSS.

The Simulation Execution subsystem (see chapter 4) loads the scenario, handles the communication with the application and the database. It converts the object data into primitives (points, lines, faces, and shadow faces) which are sent to the Image Generation subsystem.

The Image Generation subsystem (see chapter 5) produces the image from the primitives supplied by Simulation Execution. Textures are mapped onto the appropriate polygons, the polygons are scanned line by line, and the lines are rendered into an image buffer. Shadows are added and anti-aliasing techniques are used for the final image.

The on-line part of the RTSS is designed to be scalable. Computational intensive processes (e.g., database handling, scan conversion, texture mapping, shadow generation) are done in parallel. The number of parallel processes is variable and determines the power of the system.

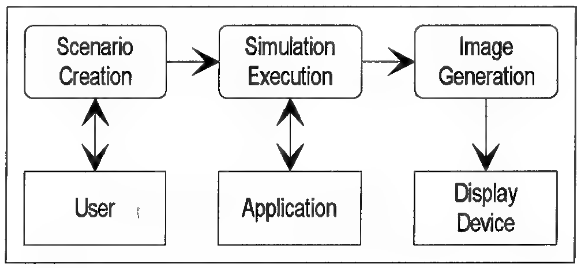

Figure 2: RTSS Architecture

3. SCENARIO CREATION

Before a simulation can be executed, the scenario of this simulation has to be defined using the scenario creation tools. These tools provide means to import object models from external modellers, to edit the characteristics of the objects contained therein, and to edit the scenario itself. Scenario creation is done off-line on a host computer.

3.1 Import Filters

The *import filters* provided in RTSS enable a user to import geometric object models created by existing commercial modellers. The imported model data is converted into the internal format used by RTSS keeping as much of the semantics of the model as possible. Currently, RTSS supports models made using MultiGen in the Flight format as well as AutoCAD.

3.2 Object Editor

The user can interactively modify the visual characteristics of an object using a built-in *object editor.* This editor consists of two parts: a material editor and a texture editor. The material editor can be used to combine several characteristics of materials. A material defines transparency, lighting type (emitter or reflector), shading type (Flat, Gouraud, or Phong), and reflection coefficients for ambient, diffuse, and specular lighting. In the texture editor, the user can change the material of each surface of an object and apply textures to these surfaces.

3.3 Scenario Editor

Using *the scenario editor*, the user finally specifies the scenario contents. It contains the initial position of the elements (*assemblies, cameras,* and *light sources*) in the scene. An assembly is a hierarchically organized set of objects with fixed relative positions. For an assembly, the user can specify whether it is shadow casting and visible or not and its collision detection list. During simulation,

the assembly is tested for collision with all assemblies identified in this list. The user can define the type of a light source (ambient or directional) and the values corresponding to this type. For a camera, a user can define its aperture angle, view direction, and clipping planes.

Most of the properties of the elements can be changed during run time. Therefore, the scenario editor enables a user to specify whether during simulation changing the properties is allowed (element type is *dynamic*) or disallowed (element type is *static*). Apart from the properties of the elements, the scenario also contains global information, so-called *session parameters*. These include parameters for the lighting model, screen resolution, depth cueing, background colour, initial camera, and settings for switching on/off edge anti-aliasing, texture anti-aliasing and shadow generation. The depth cueing parameters as well as the background colour can be changed during run time. While defining the scenario, the user can inspect the scene using a 3-D viewer. This shows the scene from a global view point or from the view point of the initial camera. In this scene icons indicate the position of light points and cameras.

4. SIMULATION EXECUTION

The Simulation Execution subsystem is responsible for the interface to the application and the handling of the database. The individual modules of the subsystem are shown in Fig. 3.

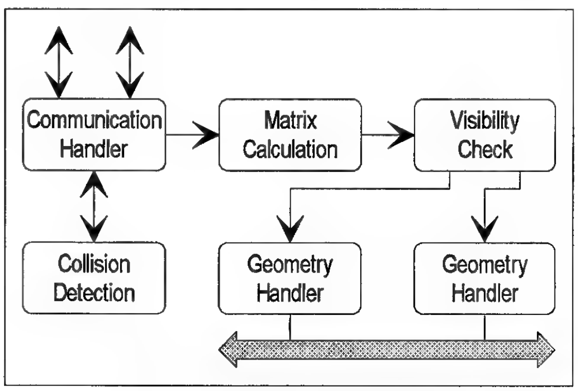

Figure 3: Structure of Simulation Execution

4.1 Interface to Application

The interface to the application is a bi-directional channel. At the begin of a run, the application sends the name of the scenario to be used, which is then loaded from files (thus, not through the application). During run time, the application sends commands. Commands are:

- parameter changes: lights, background colour, depth cueing;
- camera changes: position, orientation, parameters;
- movement data: position, orientation, and scale of objects;
- object data: colour and material of objects;
- collision detection: which object pairs are checked for collisions.

Commands have to be issued in a specific protocol. There is no restriction on the timing of the commands, since the reception is decoupled from the rest of the system. Therefore, they may be sent at any time.

RTSS in turn sends back the result of the collision detection. Collision detection, and thus the feedback, can be switched off it it is not needed.

4.2 Collision Detection

The Collision Detection module is an optional part of the RTSS. It detects overlapping geometries of objects on polygon level, i.e., the module reports polygons of different objects that intersect each other. For each assembly it can be specified with which other assemblies collisions are checked. This can be used to reduce computation to the interesting objects (one space ship making contact with another) and to avoid unnecessary collision reports which will occur in any case (a car moving on the street). Collision Detection is decoupled from the rest of the system (for input as well as output), i.e., the reports to the application are not coupled to the frame rate.

4.3 Database

The whole database is distributed over a number of processors, the *Geometry Handlers*. During a frame the *Visibility Check* issues object identifiers of visible objects and shadow casting objects to the respective Geometry Handler. Objects not visible in the image or not casting a visible shadow are discarded as early as possible. The Geometry Handler converts the object into primitives (points, lines, faces, and shadow faces), transforms these primitives to the correct coordinate system, and clips them against the view volume. The lighting model is evaluated for vertices and faces. For shadow casting objects shadow volumes are calculated and decomposed into shadow faces. All primitives are collected in a buffer and broadcasted over a bus to the Image Generation subsystem upon a system synchronization signal. For details of the algorithms see [1].

The number of the Geometry Handlers is a parameter of the system design. Systems using small databases need only one or two Geometry Handlers, while systems using big databases can use many. The number is not limited by software or hardware restrictions.

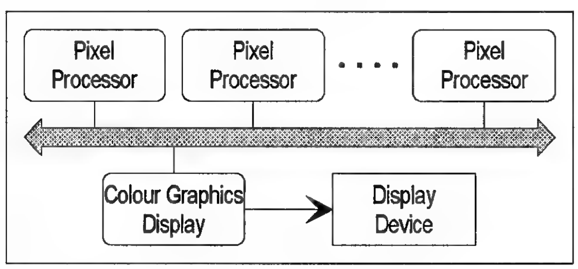

Figure 4: Structure of Image Generation

5. IMAGE GENERATION

5.1 Operating Principle

The output image of RTSS is divided into a number of horizontal *scan lines*, each of which is divided into a number of *pixels*, thus forming a rectangular raster. The Image Generation process is responsible for the determination of the colour of every individual pixel. This is based upon the *render primitives*, which are the output of the Simulation Execution subsystem (see chapter 4). First, all the render primitives are rendered in the *frame buffer*. Then all the shadow face descriptions are processed into a separate *shadow buffer*. Finally, the frame and shadow buffer are merged into the final *image buffer*. If there are no shadows present in the scenario, the last two stages are skipped and the frame buffer is considered to be the image buffer.

5.2 Parallel Processing

The computations involved in Image Generation are the most time consuming of RTSS. Therefore, an efficient way of decomposing this process into parallel tasks is required. The decomposition of Image Generation is shown in Fig. 4

The output image is divided across the processors executing Image Generation (these processors are called *Pixel Processors*) in a *scan line interleaved* fashion. Suppose the number of pixel processors to be N. Pixel processor i (with $i < N$) 'owns' scan line i and then $i + N$ and so on. This way, every pixel processor has roughly the same number of scan lines (and therefore pixels) to compute, thus guaranteeing a uniform workload.

The primitives are received via a bus to which all Pixel Processors, as well as the Geometry Handlers, are connected. After every Pixel Processor has finished, the partial images are gathered in the video memory of the Colour Graphics Display for display. This gathering is done across the same bus. The number of Pixel Processors can be adapted to the required performance of the system. It is not limited by software or hardware restrictions.

5.3 Algorithms

Visible priority of occluding primitives (also called Hidden Surface Elimination, HSE) is treated using the *z-buffer* algorithm. Almost all major visual systems use this (or adaptations of it) for HSE. The algorithm has the advantages that it is

- Independent of the order in which the primitives are treated. This is of particular importance in the RTSS case, because a global priority ordering of the primitives (which would be needed otherwise) can not be performed by the Geometry Handlers (when implemented on more than one processor). Therefore, this ordering would have to be executed by the Pixel Processors, which is are already heavily loaded with work.
- Capable of handling all sorts of render primitives.

To prevent disturbing noise in the image, two forms of anti-aliasing have been applied:

- Lines and the edges of polygons are smoothened using the *a-buffer* algorithm, described in [2]. This technique filters the well known 'staircase jaggies'. We have chosen this method from a number of alternatives, because it is suited for a z-buffer set-up, only uses extra computing power for filtering of the edges, is independent of the sub-pixel resolution used, and does not require a major amount of extra memory.
- A technique called *mipmapping* is used to filter the inside of *textures.* Almost all commercial visual systems which incorporate texture anti-aliasing use mipmapping. Refer to [3] for details on this technique.

6. HARDWARE

The demands for the on-line part in terms of calculation power, communication bandwidth, and scalability, are satisfied by using parallel processing. To guarantee a long life cycle and easy expandibility the hardware developed inside the HAMLET project was used. The processor is a PowerPC connected to a T425 transputer for communication. However, the bandwidth needed to transport the primitives and the image cannot be met by transputer links. Therefore, a special bus system called Transputer Image Processing (TIP) bus is used.

6.1 Processors

The processor board TPM-MPC is equipped with a PowerPC 601 processor running at 80 MHz. An INMOS T425 transputer running at 30 MHz is used for communication along the 4 transputer links operating at 20 Mbit/s. The transputer is equipped with 4 Mb of local memory and shares 16 Mb of memory with the PowerPC. Using the transputer links, these boards can be connected in any kind of network. The PowerPC and the transputer are programmed in C using the PowerTools which are an extension of the INMOS C toolset.

6.2 Communication

The high communication demands required by the communication of the primitives (see section 4.3) and the image (see section 5.2) cannot be met by using the transputer links (about 2 Mb/s): a 512 $\times$ 512 true colour image with 25 images/s needs a bandwidth of 25 Mb/s; the respective 1024 $\times$ 1024 images needs 100 Mb/s. Additionally, the primitives are broadcasted over the bus.

The demands are satisfied using the TIP-Bus. This bus provides the hardware to transfer data from the local memory of one processor to that of another. The bus is 32 bit wide and has a peak bandwidth of 120 Mb/s. The bus architecture allows point-to-point communication as well as data broadcasting and gathering (which is needed to distribute the primitives to all Pixel Processors and to gather the partial images on the Display Processor). If necessary, the bus can be divided into several segments working in parallel.

The TIP-MPC boards are equipped with a PowerPC 601 operating at 80 MHz, an INMOS T425 transputer running at 25 MHz as the bus controller, 16 Mb of shared memory, and 2 Mb of video memory, which is the interface to the bus. Any number of these boards can be connected to one bus.

Special interface boards are available to connect the TIP-Bus to display systems or cameras. RTSS uses the Colour Graphics Display. The CGD is equipped with an INMOS T805 transputer and a video chip to drive a display device.

The CGD is also programmed in C using the PowerTools. The TIP-Bus can either be programmed directly or using a special language called TIP-Set.

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Ship Airwakes - A new Generic Model for Piloted Simulation

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SUMMARY

The disturbed airwake in the lee of the superstructure of ships with an aft flight deck causes significant control problems for helicopters operating during strong winds. Providing adequate data to describe these airwakes for use in flight simulators has been a difficult task from either wind tunnel tests or theoretical airflow estimates. In this report an empirical mathematical model is developed based on the main types of airflow pattern present in airwakes. The model uses a single set of modelling parameters to produce airwake data for any shape of ship with an aft flight deck and for any wind direction. Assessment of the model in a piloted flight simulator has been very favourable with the main criticism being the absence of turbulence, which is available in the model but could not be used because of difficulties in simulating helicopter responses at that time. Comparison of airwake estimates with a set of boundary layer wind tunnel results shows good agreement in the complex flow with the wind from starboard at 30°, and suggests some areas where adjustments to the model could improve the comparison for other wind directions.

The model has highlighted several interesting features of airwakes, including probable improvements in airwakes if hangar tops can have porous net fences around the edges, the effects of gradients in vertical airflow velocities on control of a helicopter's height, and the need to include response to flow gradients in helicopter aerodynamic models for simulation of operations in airwakes.

It is recommended that the airwake model should be validated against full scale and wind tunnel data on other shapes of ship, and, after any necessary adjustments to the model, it should be used for a trial installation on a suitable existing helicopter training flight simulator, prior to introduction into general use for R & D in helicopter/ship research programmes and for helicopter training simulators.

1. INTRODUCTION

The disturbed airwake in the lee of a ship superstructure passes directly over the aft landing areas used by helicopters on small ships, and there are also updraughts over the edges of the flight deck. In moderate and strong wind conditions from some directions these airwake disturbances can be sufficient to make it unsafe to land or take-off. The main problems arise from airwake effects such as the magnitude of a downdraught leaving insufficient power available to control descent safely, the crosswind being so strong that there is insufficient roll cyclic or rudder control to maintain the proper heading relative to the ship, and rapid changes of wind in any direction over small distances that can make it difficult to achieve the necessary precision of control needed for landing safely on a small moving deck.

Thus for any combination of ship and helicopter types there are Ship Helicopter Operating Limits (SHOLs) that specify the safe boundaries of Wind over Deck (WoD) strength and direction. These have implications for operational effectiveness because the need to provide acceptable WoD strength and direction for helicopter operations can restrict the freedom of the ship in speed and direction in moderate or strong natural winds.

Much effort both now, and over many years past, is directed to

a) improve prediction of SHOLs to aid in ship and helicopter design

b) provide simulator training for adverse WoD (and ship motion) situations.

Testing with ship models in wind tunnels has increased knowledge of airwake conditions, and attempts are being made to use the increasing power of Computational Fluid Dynamics (CFD) to generate computer models of the airflow around ships. However the complex shapes and separation of airflow around many corners make it very difficult to apply the principles of CFD and generate realistic computer models. Several papers in the proceedings of the AGARD Flight Mechanics Panel Symposium on 'Aircraft Ship Operations' held in 1991[1] addressed operational and modelling issues relating to helicopter operations from small ships.

One of the most powerful tools for developing our understanding of the relationship between complex airwakes and their effects on a helicopter would be piloted flight simulators[2]. However, a simulator can only be used to study such effects if it has a realistic model of the airwake and can satisfactorily represent the behaviour of the helicopter. It is also essential that the airwake model can provide instantaneous local wind information at the helicopter position in real-time, which in practice means it must be calculated within a few milliseconds.

Paper presented at the AGARD FVP Symposium on "Flight Simulation — Where are the Challenges?", held in Braunschweig, Germany, from 22-25 May 1995, and published in CP-577.

One way of providing such data would be to tabulate measured model data (or full scale data if available) and interpolate between the data points to the actual helicopter location. Unfortunately, model data is generally obtained at relatively widely spaced points, and flow visualisation demonstrates that there are complex changes in flow between these points that will not be adequately represented by simple interpolation. Also, such data is totally specific to the configuration tested and cannot be readily adapted to account for changes in ship structure. Eventually it may be possible to generate data maps from CFD calculations, but in the meantime there is a need for some form of mathematical airwake model that can represent the main flow characteristics in the airwake in a way that can readily account for significant structural configuration changes or even different ship types. Any empirical model will need to be validated against wind tunnel test results and full scale data. It will then provide a firm basis for studies of SHOLs, provide a representative environment for studies of operational developments such as landing aids, and also provide a model for use on training simulators.

Such a mathematical model has been developed for the Defence Research Agency with funding from the UK MoD Defence Research package 25c, and initial datasets have been tested in a piloted simulation study. This report describes the model; presents some typical examples of airflow datasets; presents data on the behaviour of a simulated helicopter in the airwake; and describes a future work programme to exploit this airwake model in training and research simulators.

2. MODELLING ISSUES

Airflow around and downstream of bluff objects is extremely difficult to model because the air cannot turn abruptly and separates from surfaces. In addition, it is also difficult to produce fully representative data from wind tunnel tests because of scale effects (mainly Reynolds number effects), physical difficulties in representing some important small features at model scale, and the sensitivity of airflow disturbances to shear and turbulence present in the wind before it encounters the ship. A concise summary of the problems and the current state of measuring techniques and knowledge is given by Garry[3].

When establishing SHOLs, both the effects on helicopter performance of average local airflow increments across the rotor, and also the effects of rates of change of airflow with distance (airflow gradients) on the control of helicopter position, need to be considered. The spacing between datapoint locations must be close enough to define average values, which requires horizontal spacing at intervals of approximately rotor radius, i.e. approximately 5m for typical helicopters that operate from small ships. Spacing must also be close enough to define gradients wherever velocity changes and gradients are both large enough to affect the control of the helicopter, such as downwind of the hangar edges in the vicinity of the ship. Definition of these gradients may require spacings of around 1m.

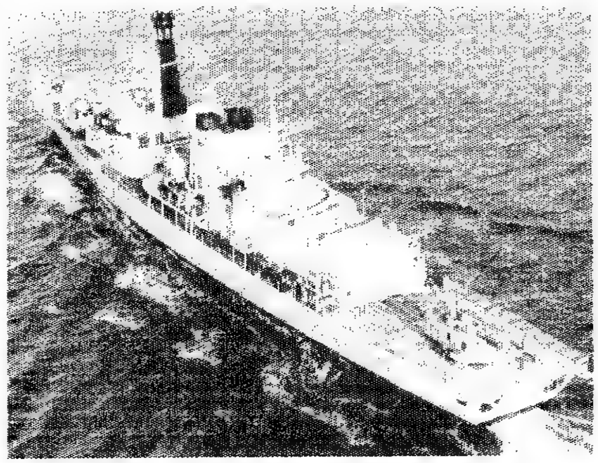


Figure 1: Merlin helicopter on the aft flight deck of a Frigate

When considering effects at this scale and greater, it is reasonable to look at empirical modelling based on the physical characteristics of the flow in order to represent the required conditions. This empirical modelling can be based on observed forms of airflow around individual body shapes and the sizes of the parts of the body geometry that dictate the scale and shape of the airflow. From this it will be possible to calculate flow disturbances for more complex body shapes.

Ship structure consists of combinations of different body shapes, e.g. hull and hangar, on a ground plane (the sea), Figure 1. Thus it is necessary to combine airflow effects from different body shapes to obtain overall flow disturbances. In general such airflow effects can only be added together in a simple way if the effects of one body component have largely disappeared before the effects of the next body component will become significant. Fortunately this is a reasonable approximation for many typical ship structures in the region of a flight deck because of the size of open area needed for aircraft operations.

An empirical approach to modelling using these assumptions is likely to provide good estimates of the main features in airwake disturbances once it has been matched against appropriate full scale and wind tunnel experimental measurements. It should also be effective in estimating the effects of changes in geometry as long as the basic assumption that effects are additive is still appropriate, which is a reasonable assumption for the present generations of ships with flight decks.

The present model is developed for disturbances aft from the forward edge of an aft flight deck (often the aft face of a hangar) and extends aft until all significant flow disturbances that might be felt during an approach

to the ship have dissipated. The principles could be applied to flat top ships (aircraft carriers) but some details and values of primary constants used in the modules would be different.

3. DESCRIPTION OF THE MODEL

3.1 General principles

A basic ship geometry with a hangar in front of an aft flight deck (Figure 2) is used to describe the structure that causes flow disturbances. It is assumed that effects from other superstructure further forward than the hangar will generate turbulence and a momentum loss but no significant discrete flow disturbances with a wavelength of 10m or more. This assumption should be examined for specific ships, but is reasonable in most cases. The model includes effects when hangar sides are not vertical, which is quite common; also included are effects of any fence(s) on the roof of the hangar, and of folded stanchions and safety netting around the flight deck.

All aircraft, including helicopters, are sensitive to ***changes*** in airflow, and particularly changes in vertical airflow. The significance of airflow patterns is often best illustrated by plotting significant disturbances to airflow as ***incremental changes*** rather than the overall airflow. This is particularly true for vertical components of airflow, where a few knots downflow require significant increases in power to prevent a helicopter descending (1kn downflow ≈ 100ft/min). As an example Figure 3 shows vector plots in a vertical plane for total vectors and disturbance vectors normalised by the WoD, where the maximum disturbance is 30% of the WoD which is horizontal. If this WoD was 30kn then the peak updraught would be 9kn (≈ 900ft/min), which is very significant, but it does not seem particularly noticeable in the total vector plot. Similarly, changes in the horizontal wind are not very obvious in the total vector plot, but they are clear in the plot of the disturbance vectors. Thus all vector plots in this report will represent disturbance vectors. The model calculates disturbances rather than total velocities.

It is important to remember that a disturbance velocity vector must be added to the free stream (WoD) vector to obtain the actual local wind vector. As a simple example there is no horizontal component of flow along the deck at the aft face of the hangar as air cannot pass through the solid surface of the aft face. Thus for WoD from the bow the disturbance velocity at the aft face of the hangar will be the same as the WoD but in the opposite direction. The total horizontal wind velocity at that point is then zero, and the disturbance vector is equal and opposite to the free stream WoD vector. In general a disturbance vector showing a horizontal component in the opposite direction to the WoD does not mean that the horizontal wind is reversed but only reduced (unless the disturbance is greater than the WoD).

Ideally, models would be developed from the results of tests to identify the effects of different shapes on the

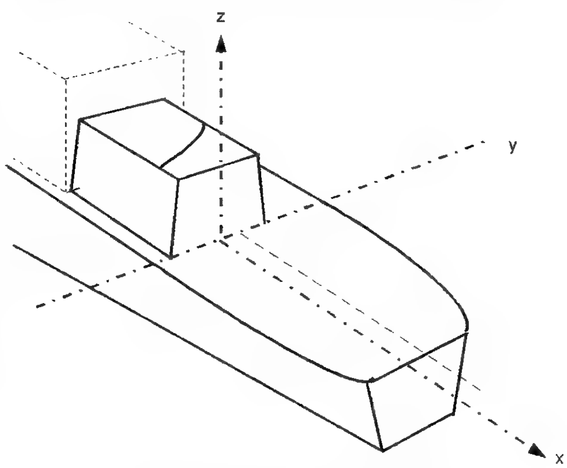
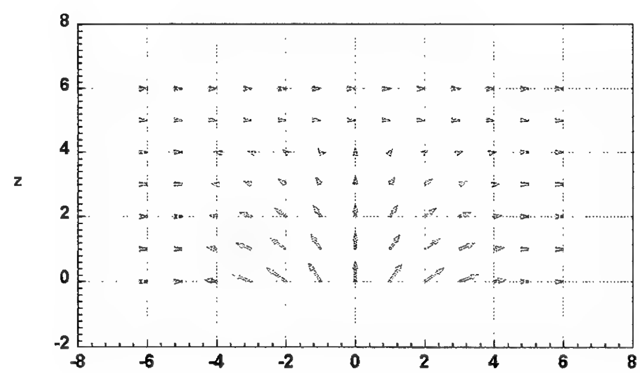
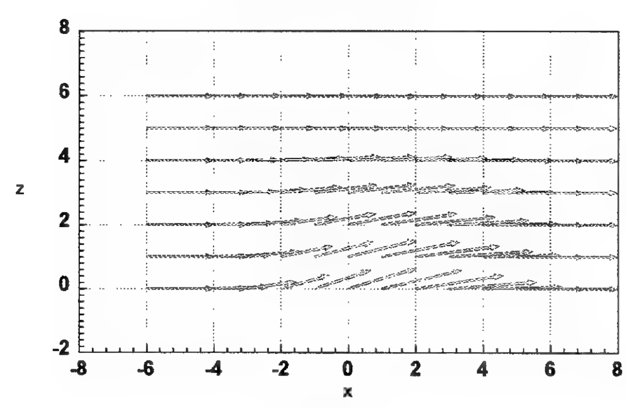


Figure 2: Basic ship structure



Disturbance vectors



Total vectors

Figure 3: Comparison of vector maps for Disturbance and Total Wind vectors

airflow downstream of relevant bluff bodies. However, there are apparently no such data for ship shapes. Whilst the majority of tests of the effects of airflow on buildings are concerned with the loads on the building, there is some limited data, which concentrates on airflow on the ground around buildings where the main interest is to avoid blowing people over. One of the most useful references is 'Wind Environment around buildings' by Penwarden & Wise[4] where some parametric data is presented. Airwake models have been developed for this present programme using the above reference as a guide in combination with interpretations of characteristic flow patterns past ships and other bluff objects shown in test results for specific shapes.

It is assumed, as is normal practice, that all velocity increments are proportional to the magnitude of the Wind-over-Deck (WoD) and functions of the relative direction of the WoD to the ship. This relationship is likely to be correct for moderate and strong winds. In light winds there may be some changes in airflow patterns but overall disturbances will be small because of the low wind strength and so will the effects on helicopters. As a consequence it will be reasonable to use estimates based on strong wind effects for training or estimation of SHOLs.

The coordinate system for incremental disturbance velocities is fixed in the ship and moves with the ship for linear translational movements (forward, lateral translation and vertical heave) and heading changes at the origin, but remains fixed relative to the earth in attitude, i.e. the axes do not move with the ship in pitch or roll. The origin is placed on the flight deck midway across the aft face of the hangar for calculating airflow disturbances. Operationally it may be more appropriate to use a system with an origin transferred to the centre of the landing circle.

Three basic flow patterns are used to estimate mean airflow disturbances plus a further pattern to satisfy the need for solid boundaries at the vertical faces of the hangar and the hull. The basic patterns are

a) **Corner flow**, which describes flow up to and around a sharp corner of a face that is across the main flow, e.g. up to the side of the hull and over the edge of the flight deck for a beam wind. This flow can be divided into two types depending on the angle between the wind and the line of the edge of the corner. If the wind is almost perpendicular, like a beam wind to the flight deck edge, then the flow is ***Separated corner flow,*** (Figure 4) where there is a stagnant region just beyond the corner and the airflow reattaches to the surface some distance downstream. If the wind is at a relatively shallow glancing angle to the line of the edge of the corner, like a wind from 30° interacting with the fore-and-aft top edge of the hangar, then on passing over the windward end of the

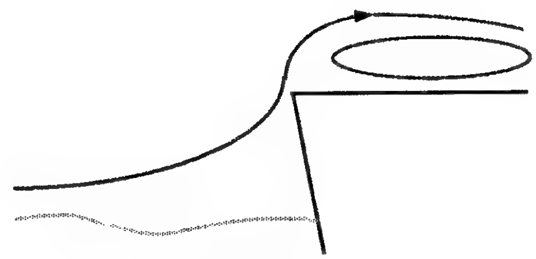


Figure 4: Separated corner flow

corner the wind forms a vortex that increases in strength along the edge and then translates downstream with the wind and decays slowly (Figure 5). This flow is ***Vortex corner flow.***

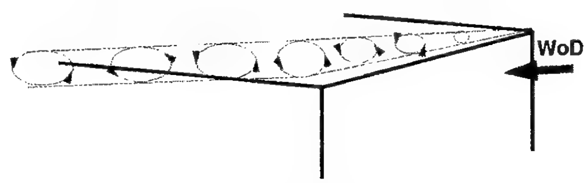


Figure 5: Vortex corner flow

b) **Lee rotor flow,** which describes the horseshoe rotor (vortex) found in the lee of bluff bodies (Figure 6).

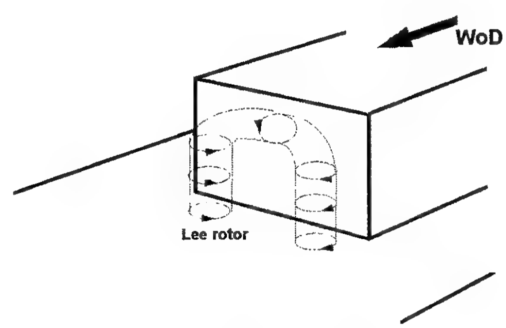


Figure 6: Lee rotor flow

c) **Profile drag flow,** which describes the loss of momentum (velocity) in the wake of bodies and is a measure of the profile drag of the body. This flow pattern can be introduced downstream of any separated flow regions (Figure 7).

The pattern needed to satisfy the need for solid boundaries is called **Inflow** and is the flow into an inlet at the solid downstream face such that the velocity through the face is equal and opposite to the component of the WoD in that direction. This flow pattern is needed to obtain zero flow through solid faces, and because neither the Lee rotor or the Profile drag flows produce perpendicular flow at downstream faces. Similarly a negative Inflow (Outflow) is needed for upstream faces.

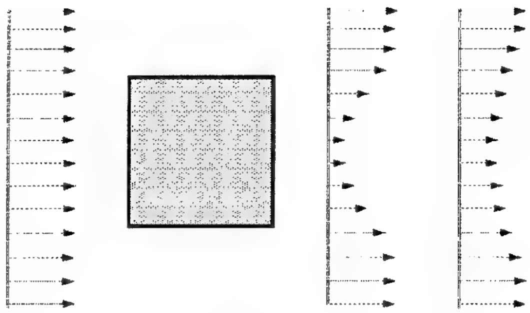


Figure 7: Profile drag flow

In addition, turbulence is added to any existing free stream turbulence and applied as time varying fluctuations to the mean disturbances.

3.2 Selecting flow pattern modules

Different flow pattern modules have to be selected according to the general direction of the WoD and the different shapes of the hangar and hull. When a small change in WoD direction requires a change in the type of flow module then it is possible that there may be a noticeable step in the total flow vectors, which is not likely to be present in real life. To avoid such steps the incoming and outgoing modules are overlapped and linearly ramped up and down respectively over a small (10°) range of direction. This overlap is not applied if the output of each module would be zero at the changeover point. In practice this means that overlap is applied around the mid point of each quadrant, i.e. WoD directions of -135°, -45°, 45° and 135°.

A full list of the flow pattern modules applied to each of the faces and corners is given in Table 1. In general, a separate version of a module is required for each of the faces or corners that it has to serve because of the different dimensions and orientation with respect to the ship of each feature. This would imply creating a total of 39 different modules. However, every Outflow module is equal and opposite to an Inflow module, and the general symmetry of the ship makes it possible to use single modules for a Port or Starboard face or corner with suitable changes of sign. With these simplifications the model could be based on 16 modules.

3.3 Turbulence

The flow pattern modules determine mean flow velocity changes, but an important airflow ingredient in aircraft operations with ships is the large variation of local wind velocity with time, which is turbulence. The effect of turbulence on an aircraft depends on the frequency of the turbulence, which can be a function of the turbulence wavelength and the aircraft airspeed as well as a function of time. Very approximately an aircraft and pilot will need to respond to wind fluctuations that have a period greater than about 2-3s to avoid significant flight path deviations. For fluctuations with periods from about 1s down to about 0.2s the effects will be seen as turbulence to which they may try to respond.

At periods below about 0.2s the aircraft response will not usually be significant in terms of flight path deviations although some accelerations may still be felt. Fluctuations with a period between about 1s and 3s are particularly important when trying to control an aircraft precisely. For a helicopter during landing or take-off these periods will be associated with turbulence wavelengths of about 10 - 100m.

It is very difficult to obtain information on the distribution of turbulence energy at different and relevant wavelengths for ship airwakes. Usually the only data available are Standard Deviations, which contain no information on the distribution of energy. For the purposes of testing this model a simple approach has been taken where a level of Standard Deviation is applied to an existing turbulence model. The Standard Deviation is varied in proportion to the total incremental velocity from the mean flow velocity model. In this way, turbulence will be greatest in regions where incremental flow disturbances are largest.

In practice the ship will be operating in a particular wind condition and there will be natural turbulence present that is related to the free stream wind strength, sea roughness and atmospheric stability. It seems appropriate to include some element of the natural turbulence in the total turbulence and this is done by taking the Root Mean Square (rms) of the natural and ship-generated turbulence. Ship-generated turbulence is proportional to the WoD strength, and this strength will depend on the combination of the natural wind and the speed and direction of the ship.

A suggested value for the Standard Deviation related to velocity increments is

$$0.4 \times (\text{Total local velocity increment}),$$

i.e. total rms turbulence is given by

$$\begin{bmatrix}\text{rms}\\ \text{turbulence}\end{bmatrix} = \sqrt{\begin{array}{l}[\text{Free stream rms turbulence}]^2\\ +[0.4 \times (\text{Total local velocity increment})]^2\end{array}}$$

Unfortunately it has not yet been possible to verify this value, or the simplified approach to turbulence representation, because the available helicopter simulation model and turbulence models did not produce helicopter disturbances that were recognisable as normal responses by a helicopter in flight through turbulence. Improvements in the simulation of helicopter responses to turbulence are being actively pursued. An appropriate response to turbulence is an essential ingredient in the simulation of ship operations with a representative airwake.

Table 1: Flow patterns used for surfaces and edges at different WoD directions

Port — **Wind over Deck Direction** — **Starboard**

Vertical faces and Edges

		-180° to -135°			-135° to -90°			-90° to -45°			-45° to 0°			0° to 45°			45° to 90°			90° to 135°			135° to 180°		
Hangar	Port	S	O	-	-	O	-	-	O	-	-	O	-	L	I	P	L	I	P	L	I	P	S	I	P
	Starboard	S	I	P	L	I	P	L	I	P	L	I	P	-	O	-	-	O	-	-	O	-	S	O	-
	Aft	-	O	-	-	O	-	S	I	P	L	I	P	L	I	P	S	I	P	-	O	-	-	O	-
Hull	Port	S	O	-	-	O	-	-	O	-	-	O	-	L	I	P	L	I	P	L	I	P	S	I	P
	Starboard	S	I	P	L	I	P	L	I	P	L	I	P	-	O	-	-	O	-	-	O	-	S	O	-
	Stern	-	O	-	-	O	-	S	I	P	L	I	P	L	I	P	S	I	P	-	O	-	-	O	-

Horizontal edges

		-180° to -135°	-135° to -90°	-90° to -45°	-45° to 0°	0° to 45°	45° to 90°	90° to 135°	135° to 180°
Hangar top	Port	S	S	S	V	-	-	-	-
	Starboard	-	-	-	-	V	S	S	S
	Aft	S	V	-	-	-	-	V	S
Flight deck	Port	S	S	S	S	-	-	-	-
	Starboard	-	-	-	-	S	S	S	S
	Stern	S	S	-	-	-	-	S	S

Legend:
S Separated corner flow, V Vortex corner flow, L Lee rotor flow,
O Outflow, I Inflow, P Profile drag flow

N.B. Thick grey lines indicate overlap regions

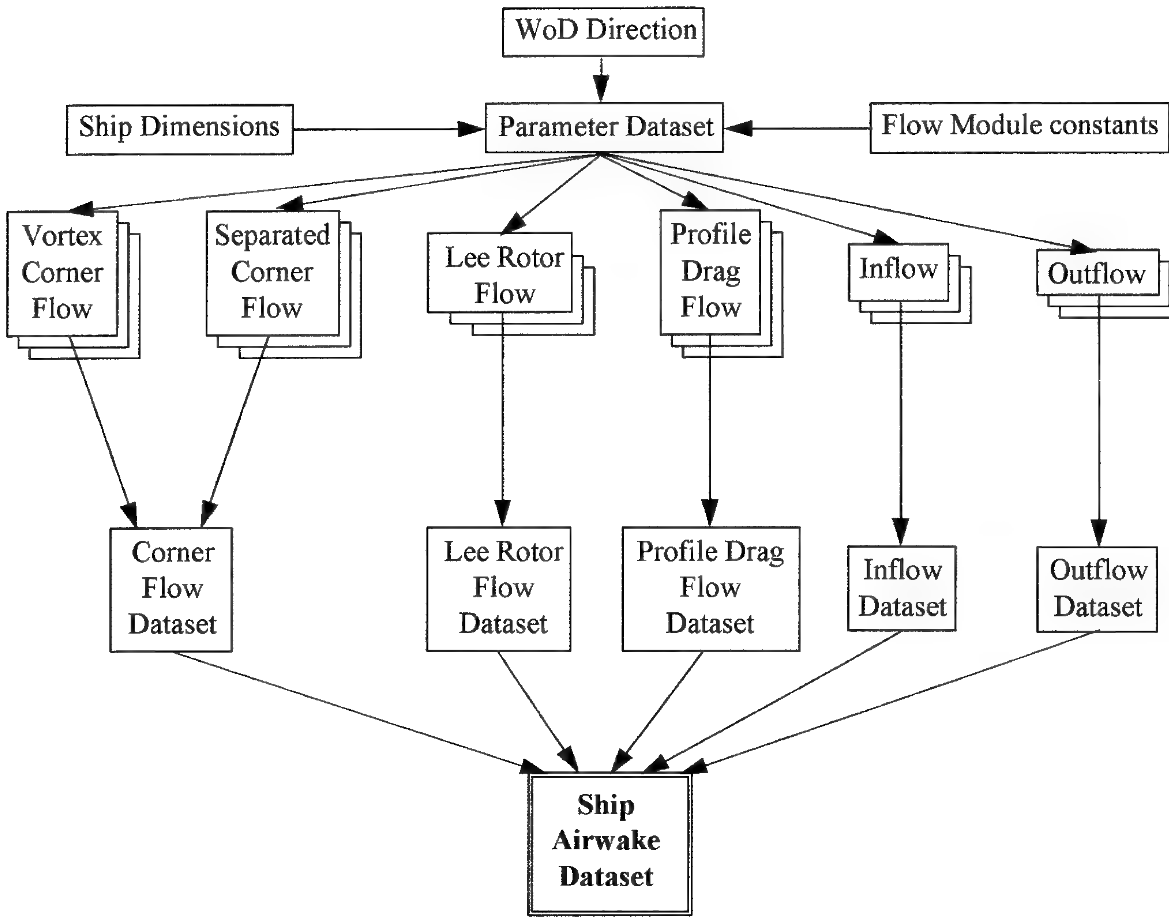


Figure 8: Airwake model structure

4. RESULTS FROM THE AIRWAKE MODEL

4.1 Overall model structure

The overall model structure is shown in Figure 8. Flow Module constants are determined during verification of the model and then remain fixed for all ship dimensions on ships with aft flight decks and for all WoD directions. Ship dimensions are defined once for a given class of ship. Details of the required dimensions are given in Table 2. The final input variable is WoD. Each of the 16 individual modules then calculate flow velocity increments in axes related to the part of the structure to which it refers. When all of the modules for a particular type of flow have been calculated then the velocity increments are converted to ship axes and added together in a dataset for that type of flow. Finally all the 5 datasets for the different flow types are added together to obtain the overall ship airwake dataset. An example of wind increment data in a transverse vertical plane through the landing circle for WoD from Port 30° is shown in Figure 9.

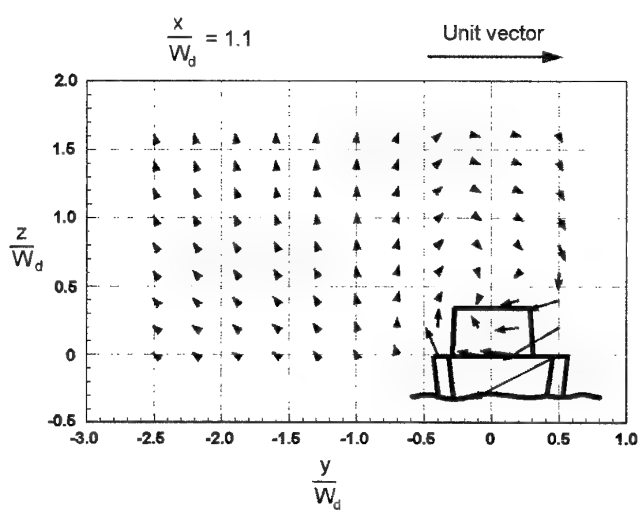


Figure 9: Airwake increment vectors with WoD from Port 30°. Transverse plane.

Table 2: Ship dimensions

	Symbol	Description	Example value
Flight Deck & Hull	W_d	Datum Length. Beam width of the deck at the aft face of the hangar.	15.5m
	L_d	Flight deck length	24.4m
	W_t	Width at stern end of the flight deck, or effective width using an average deck taper angle.	12.0m
	H_d	Height of flight deck above mean sea level	4.8m
	d	Offset of hangar centreline to starboard of the flight deck (ship) centre line	-1.0m
	$\gamma_d + 90$	Included angle between the flight deck and the upper portion of the side of the hull	90.0°
	$\gamma_t + 90$	Included angle between the flight deck and the upper portion of the stern	-
Hangar	W_h	Width of the hangar top	8.8m*
	L_{hs}	Length of the hangar on the starboard side	18.9m
	L_{hp}	Length of the hangar on the port side	12.6m
	H_h	Hangar height above the flight deck	5.8m
	F_s	Hangar roof fence position forward of the aft end of the hangar, starboard	7.9m
	θ_{Fs}	Hangar starboard roof fence angle aft of perpendicular to the edge	30.0°
	F_p	Hangar roof fence position forward of the aft end of the hangar, port	4.0m
	θ_{Fp}	Hangar port roof fence angle aft of perpendicular to the edge	0.0°
	$\gamma_h + 90$	Included angle between the hangar roof and hangar side	96.9°

* W_h = 14.1m for the 'Full Width Hangar' test case

5. COMPARISON WITH WIND TUNNEL TEST DATA

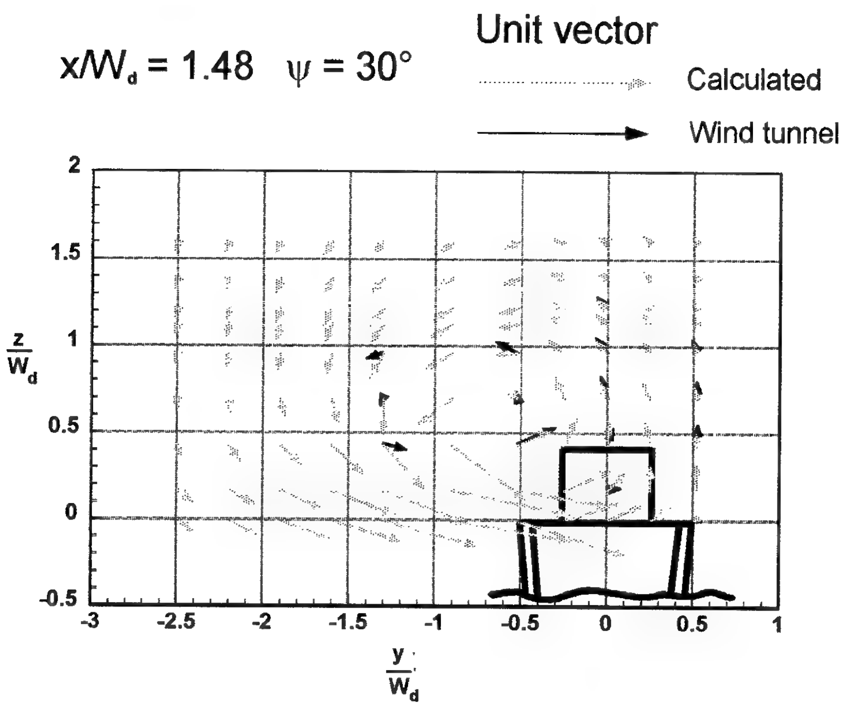
It is essential that an empirical model such as this is validated against as wide a range of measured data as possible. Measurements on and around real ships with aft flight decks would be most appropriate, but data is limited to a few measurements from flight decks using masts. Measurements with model ships in wind tunnels are much more extensive, although there is often only limited representation of small yet significant features such as safety netting and stanchions around the flight deck and many items of equipment mounted externally on all parts of a ship. Thus in general wind tunnel measurements will not be completely representative of actual flow around a ship.

However, wind tunnel measurements are the most extensive data source for airflow in locations that are not over the ship and experience has shown that these measurements can identify many major features of the disturbed airflow. Thus initial validation of the model and some adjustment of parameters have been made using wind tunnel measurements from a model of a typical frigate[5]. Data from Ref. 5 have been analysed to obtain incremental velocity ratios in the same axis system as the airwake model described in this report, and calculations of airflow increment ratios have been made for the ship dimensions of the model used in Ref. 5. There are typically 41 measuring points for a particular configuration with the wind tunnel model, which is relatively extensive coverage. However it is sparse coverage when compared with 1287 points from the airwake model. With this number of points the horizontal spacing in the airwake model is typically about 3m at full scale, and in the wind tunnel measurements it is 6 - 9m. Calculation points have been

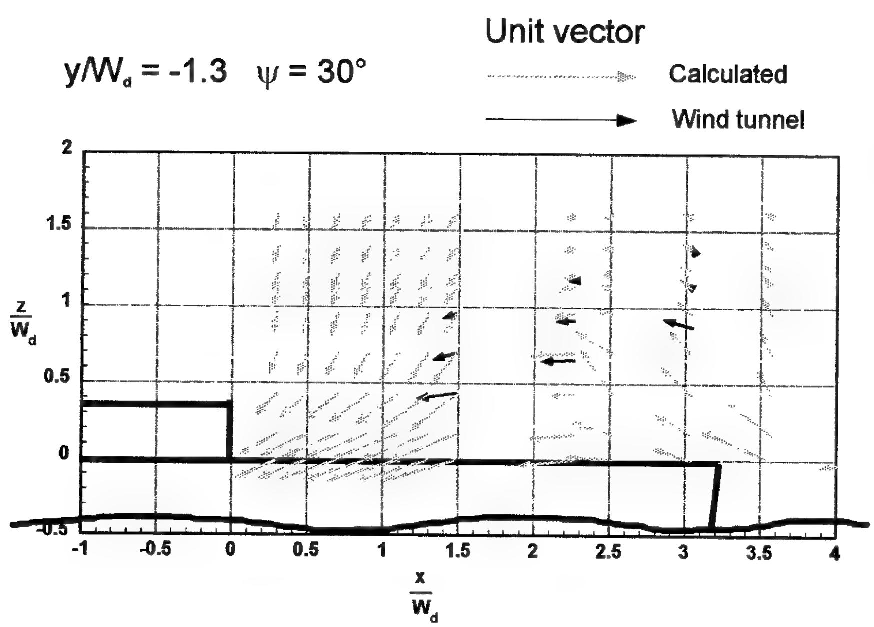
adjusted to coincide with locations used in the wind tunnel to help with comparison between data. This has resulted in some wider than usual gaps in data in the fore-and-aft direction, which are not typical of the calculated data used for simulation studies.

In complex flow conditions with a WoD from Starboard 30°, where all the different types of flow are present in the airwake model, there is good agreement between wind tunnel data and the calculated airflow increments in vertical planes at the landing circle (transverse plane) and in the approach plane to port, Figure 10. The horizontal components are very similar throughout. The vertical components are very similar except in the approach plane abeam of the landing circle where the calculated vertical velocities are significantly greater downwards than the model data. The vortex flow from the hangar roof is clearly seen in the model data in the transverse plane and is in the same location as the vortex in the calculated data. The greater downflow in the calculated data in the approach plane may be a result of too strong an inflow contribution and too much reduction in vertical component from separated corner flow above the maximum streamline.

Data comparison in a horizontal plane, Figure 11, confirms that horizontal components are in close agreement at all points of comparison including abeam of the landing circle at $x/W_d = 1.48$.



a) Transverse plane



b) Approach plane

Figure 10: Comparison of estimates with wind tunnel data for WoD from Starboard 30°

6. PRELIMINARY EVALUATION IN A HELICOPTER FLIGHT SIMULATOR

One of the important uses for an airwake model will be in flight simulators for training and for R & D studies of helicopter operations with ships. Thus part of this development programme included trials with a preliminary form of the model using a helicopter simulation on the DRA, Bedford, Advanced Flight Simulator. This was the first study of an airwake model with a helicopter simulation model and the aim was to see if the main disturbances experienced in helicopter operations with a frigate type of ship are represented and that the size of disturbance is similar to that

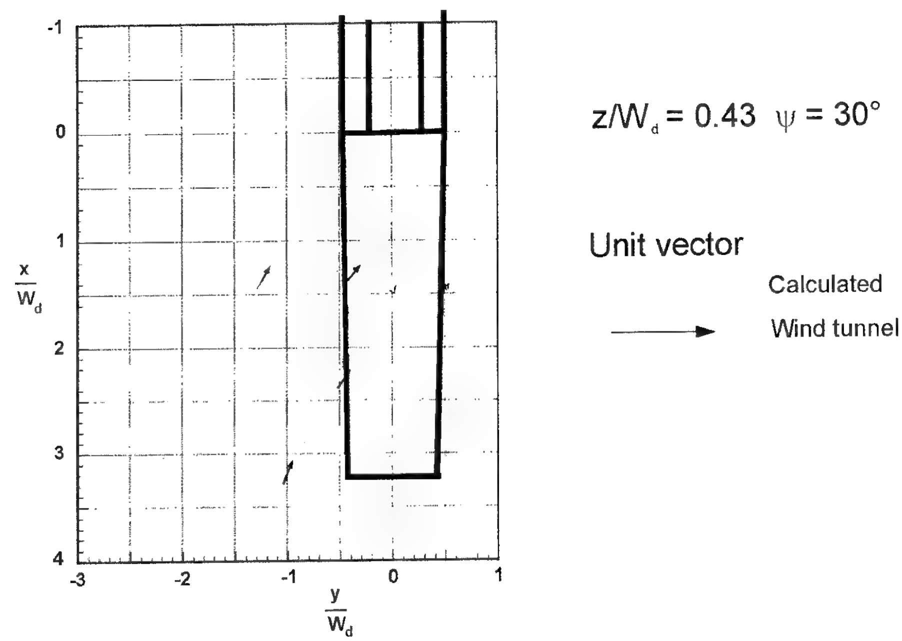


Figure 11: Comparison of estimates with wind tunnel data for WoD from Starboard 30°. Horizontal plane

experienced in real operations. A simulation of a Westland Lynx helicopter was used for the trial. The airwake model was Version D, where the main features were represented to a standard that was acceptable for an initial simulation study. Development continued during and after the trial and the latest version described in this report is Version F.

6.1 Trial conditions

The trial used the Advanced Flight Simulator at DRA, Bedford with a good representation of the handling and performance of a Westland Lynx helicopter with autostabilisers engaged. The computer generated visual scene provided a representation of a frigate with dimensions very similar (although not identical) to those provided by the DRA for modelling airwake flow increments. The differences in dimensions were not significant for this initial study where the emphasis was on comparing the main effects of the airwake on helicopters.

It was decided not to include ship motion so that the trials pilot, who was a qualified Royal Navy Test Pilot with recent practical experience of operating a Lynx from a frigate in bad weather, could look for expected (and unexpected!) disturbances without the additional workload from operating with a heaving, pitching and rolling ship.

It had been hoped to include turbulence with the airwake model, but an initial investigation showed that the combination of the helicopter model and the representation of natural turbulence in use at the time produced an unrepresentative response from the helicopter in roll and lacked the expected hard-edged effects in normal acceleration that are experienced in flight through turbulence. In these circumstances it was decided not to include turbulence with the airwake model for these initial trials. Turbulence is an important part of an airwake and will need to be included in simulator trials as soon as basic problems of simulating helicopter responses to turbulence are overcome.

Four WoD directions were selected for the trial to represent distinctly different flow situations, and strength was set at a level that would be expected to cause significant handling difficulties without preventing operations, viz. a 40kn wind on the bow and at starboard and port 30°, and a 30kn wind from the starboard beam.

6.2 Airwake datasets for simulation

Datasets for use in the simulation were provided as tables of each of the wind increment ratios in beam and vertical co-ordinates, and stepping aft in increments. Beam co-ordinates for this trial started just outside the

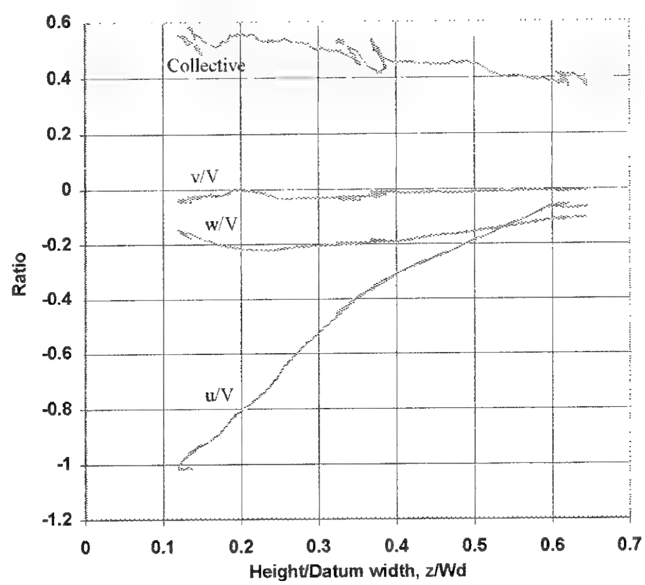


Figure 12: Vertical descent behind the hangar with 40kn WoD from ahead.

starboard edge of the deck and went to 2.5 beam units (39m) to port of the hangar centre line. Vertical co-ordinates started at deck level and went up to 1.6 beam units (25m), and aft co-ordinates started at 0.3 beam units (5m) aft of the hangar aft face and went to 2.7 units (42m). Spacing was 0.2 units aft and vertically (3m) and 0.3 units across the beam (4.7m). (Equal spacing was used in this preliminary model, but it is possible, and will often be preferable, to use unequal spacing so that data are closely spaced in regions were they are changing rapidly with distance, and wider spaced where changes are slower.)

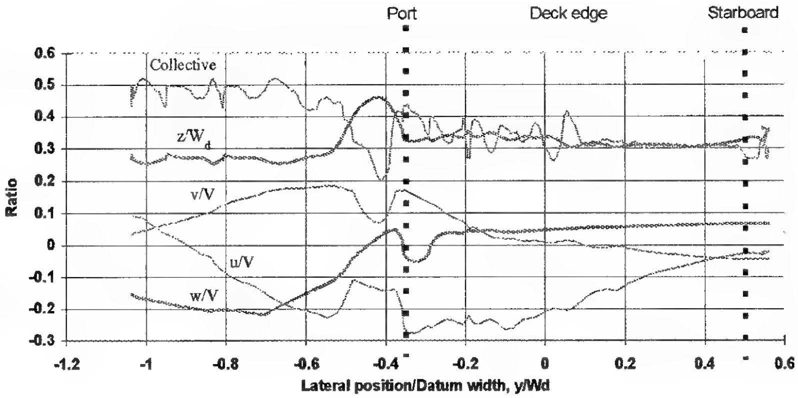


Figure 13: Lateral translation from starboard to port at a low height with 40kn WoD from starboard 30°.

To ensure that there were no significant disturbances outside the modelling envelope, additional points were added to produce values of zero increment and zero gradient at the port, aft and top edges of the envelope. For this initial trial the data values at the forward and starboard edges, and at the flight deck height in the modelling envelope were extended forward, to starboard and down to the sea. This ensured that there was no sudden change when moving into these areas, although it was not intended to use these regions during the study.

With these additional boundary points there were a total of 2688 locations with three airflow disturbance increment ratios at each point. Values at intermediate points were calculated by linear interpolation and total wind components were then obtained by adding the appropriate component of WoD. Finally, these total wind components were transformed from the ship based axes to helicopter axes, which are the axes of the equations of motion.

6.3 Trial results

Tests at each WoD condition included general flying in the regions of the normal approach path and over the flight deck, and then specific recorded manoeuvres such as climbs and descents and lateral translations at constant height. The pilot was asked to comment on the effects that he experienced and the control corrections he had to make, and to compare these with his real life experiences. Overall he was pleased with the representation of airflow conditions over and around the ship. Changes in collective control due to downflow and due to reductions in airspeed were as expected both in the places where the changes occurred and in the magnitude of the changes.

The variation of airflow increment ratios and collective control position during a vertical descent from above the hangar over the centreline and about 0.9 beam units aft in a 40kn WoD from ahead are shown in Figure 12 plotted against the vertical height in beam units. The collective increases from 40% to 55% as the helicopter descends into the lee of the hangar and the downflow, w/V, increases from 0.1 to 0.22.

A plot of the same parameters and height against lateral position in beam units, Figure 13, for a lateral translation from starboard to port at 1 beam unit aft of the hangar and at a low height in a 40kn WoD from starboard 30° shows a more complex variation of airflow increments. In particular the vortex from the hangar roof produces rapid changes between lateral positions of -0.3 and -0.7 beam units. Rapid changes in downflow from the vortex cause the brief bob-up of 0.1 beam units at around -0.4 beam units just before reaching the port edge of the deck.

During the lateral translation, Figure 13, the vertical flow is an upflow of 0.06 over the starboard side and centre of the deck. Just before reaching the port edge of the deck there is a brief region where the vertical airflow falls to -0.05 and then rises again to +0.05 before falling rapidly to -0.22.

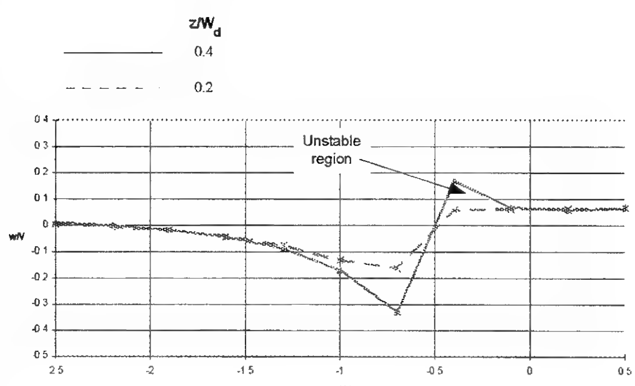
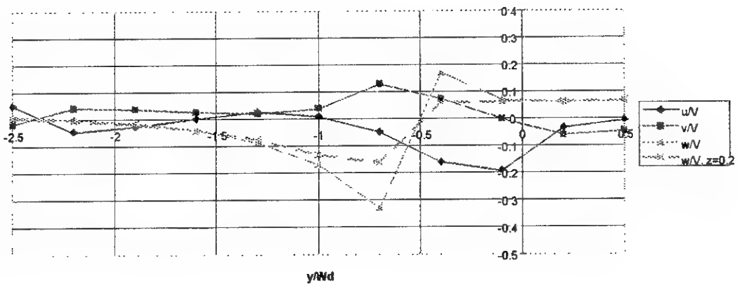
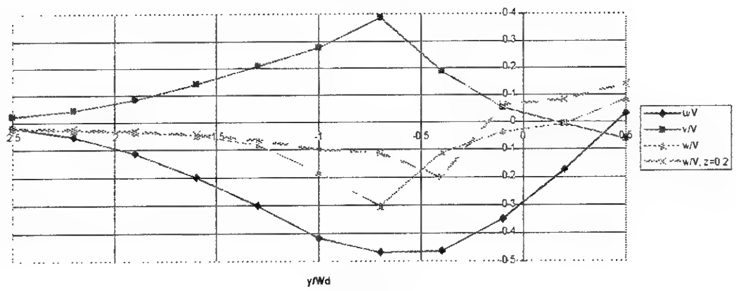


Figure 14: Unstable vertical flow region during lateral translation.

The bob-up occurs in a small region where vertical flow becomes more positive with increasing height, which makes the region statically unstable. This can be seen from the difference between the vertical component of the airflow at $z/W_d = 0.2$ and 0.4 in Figure 14, where there is a greater downdraught at a height of $z/W_d = 0.2$ than at 0.4 in the region around $y/W_d \approx -0.4$. Improvements in the Airflow Model between Version D, Figure 15a, which was used during the simulation trials, and Version F, Figure 15b, described in this report increases the effects of the inflow component of the flow, but there is still a small region around the port edge of the deck at $y/W_d \approx -0.4$ in Figure 15b, which will tend to produce a brief bob-up of similar size. This region is on the upwind side of the vortex cornerflow from the starboard hangar roof edge. At smaller WoD angles from starboard or port the bob-up region will be over the deck, which may increase handling difficulties in the landing area although the strength of the vortex will decrease at smaller WoD angles and reduce the level of static instability.



a) Version D



b) Version F

Figure 15: Flow increment ratios vs lateral position with WOD from Starboard 30° at x/Wd = 1.1 and z/Wd = 0.4

There were three aspects of the behaviour of the helicopter in the simulated airwake where the pilot wished to see improvements

i) representation of turbulence, which is an essential part of ship airwakes and helicopter handling problems, but had to be removed from the airwake model because the simulation could not adequately represent the behaviour of the helicopter in turbulence,

ii) changes in mean airflow in the model appeared too gradual, particularly around the edges of the hangar

iii) changes in pitch attitude in moving from the lee of the hangar into free stream were too small, or perhaps too gradual. (It was too easy to maintain fore-and-aft position.)

The first aspect is not a problem with the airwake model. The last aspect could be due to errors in the simulation of the drag of the helicopter at speeds below 50kn, or a combination of drag errors, a too gradual change in fore-and-aft wind increments, and too small a difference in these increments between the lee of the hangar and regions that are more exposed to the free stream wind.

Analysis of data from the simulation trials indicates a change of about 1° nose down in pitch attitude between about 10kn airspeed and 40kn, which is similar to changes present in flight. Thus the drag of the helicopter is not a cause of the problem.

The change of pitch attitude with airspeed is approximately proportional to the square of the airspeed and the airspeed is already around zero in the lee of the hangar. Thus it is unlikely that changes in the fore-and-aft airflow increment will affect pitch attitudes, and it would seem likely that this problem is associated with the rate of change of airspeed with position. This rate of change could be too gradual either because of the airflow model construction or because calculation points are too widely spaced and smooth out rapid changes.

It is also possible that the effects of gradients in airflow across the main rotor are significant and these were not included in the simulated helicopter. Gradients of vertical airflow could be particularly significant in producing roll and pitch moments. Such gradients will also be present in turbulence.

6.4 Implications of airwake model developments since the simulation trials

There are significant changes between Version D of the model that was used to calculate datasets for the

simulation trial and the current Version F. None of the changes is expected to affect the main conclusions of the pilot from the initial simulation, but the significant increase in airflow increments in some locations may result in new comments. A comparison between the two versions for WoD from starboard 30° is shown in Figure 15. The maximum downflow is almost identical and at the same location for both versions, but detailed variations in downflow are different. The maximum crossflow and loss of fore-and-aft flow are about twice the magnitude in Version F. The unexpected small changes in crossflow and fore-and-aft flow between $y/W_d = -2.2$ and -2.5 in Version D has disappeared in Version F.

Helicopters are very sensitive to vertical flow changes, are sensitive to crossflow, and are less sensitive to fore-and-aft flow at low airspeeds. Thus effects on a helicopter from the greater crossflow and fore-and-aft flow may not be as dramatic as the differences in airflow suggest.

7. AIRFLOW INCREMENTS WITH A FULL WIDTH HANGAR

Increasing the width of the hangar in the wind tunnel model tests of Ref. 5 significantly increased the downflow and crossflow angles measured over the deck. Airflow increments have been calculated for the ship example described in Table 2 but with the width of the hangar increased to occupy the full width of the ship, i.e. a width of 14.1m compared with 8.8m. The airflow increment ratios at $x/W_d = 1.1$ and $z/W_d = 0.4$ shown in Figure 16 for a full width hangar and a WoD from starboard 30° can be compared with those in Figure 15b.

The region with statically unstable vertical flow conditions is much wider and twice the level of instability. It is also much nearer to the landing point, which is at $y/W_d = 0$. This would be expected to make it significantly more difficult to control height over the port side of the deck than it is in the case with the narrower hangar. The magnitude of the downflow over the port side of the deck has also increased a little and the loss of fore-and-aft component of airflow is a little larger; these will combine to produce a greater downward flow angle as noticed in the wind tunnel tests. However it should be noted that it is the actual downflow that is significant to the helicopter performance rather than the flow angle. Crossflow over the port side of the deck is also stronger and compares with the wind tunnel increases in crossflow angle.

Thus the main effects of the wider hangar are to move the vortex from the hangar roof edge to starboard as the edge is further to starboard, which increases the region of static instability from the vertical airflow component, and to widen the region where significant crossflows and loss of fore-and-aft flow occur.

8. DISCUSSION

In this section some important implications for the helicopter/ship dynamic interface are identified, and this is followed by discussion of some implications for future wind tunnel model tests and for modelling of helicopter flight behaviour.

8.1 Important implications arising from Airwake estimation model data

This study of contributions from particular ingredients in air flow patterns provides insight into some significant features of ship airwakes that may not previously have been obvious. Two such features are the significance of rates of change of airflow increments with position in the wake (airflow gradients) and vortex corner flow.

8.1.1 Airflow gradients

If the rate of change of an airflow increment with its direction is positive then pilots will experience difficulties in maintaining position in that axis. This is particularly true in the vertical direction. If the vertical gradient is positive then any upward movement of a helicopter will produce an upward increment of the vertical airflow and the pilot will require a larger change in collective to stop his movement than to start. This will make it more difficult to control the height of a helicopter. Similar effects will occur in fore-and-aft and lateral directions and affect the control of horizontal position.

Because gradients are important it becomes necessary to locate measuring points much closer together in regions with changing gradients. If spacing of data points is too large then the apparent gradient is reduced. This could be the reason for the pilot's comment that changes were too gradual in regions such as downwind of hangar

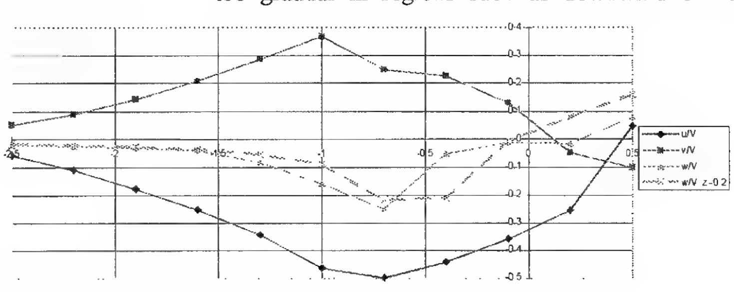


Figure 16: Full width hangar: Flow increment ratios vs lateral position with WoD from Starboard 30° at x/Wd = 1.1 and z/Wd = 0.4

corners. Spacing of around 1 - 2m would be more appropriate in regions with rapidly changing gradients.

8.1.2 Vortex Corner flow

Vortex Corner flow produces significant localised increments in airflow and gradients. It would be better for helicopter operations if it did not occur. In practice it is not always clear whether a vortex is present from measurements over a flight deck. However, it is relatively easy to inhibit the formation of a vortex by using netting similar to the safety netting around the flight deck as a fence around the top of the hangar and attached very close to the edge. The fence can be the normal height and it is essential that the netting is an open mesh otherwise it can act as a solid fence and generate a vortex from the top of the fence. The model tested in Ref. 5 included a case representing a canvas fence around the top of the hangar and this generated a full vortex.

A netting fence will also reduce the local wind on the top of the hangar, which will improve the environment for anyone who has to be in that area.

Because flow from a vortex is a significant ingredient in an airwake, it is important to establish whether it is a feature of a particular ship. This can only be established from measurements on the full scale ship, as its existence will depend on detailed features around the corner between the side and top of the hangar.

8.2 Wind tunnel model testing

Development of the airwake estimating model has highlighted some features of ship model testing that should be considered when planning further wind tunnel tests. Such tests will remain an important part of programmes to measure likely ship airwake environments and study the implications of changes in geometry on airwakes. Because of the importance of vortices in airwakes it is essential that detailed features such as safety netting and stanchions, which will inhibit the formation of vortices, are represented on models and have appropriate levels of porosity. Also, measuring points should be much closer together in regions of strong shear, because of the significance of gradients of flow increments, which can be particularly large in these regions. Positions as close as 1 or 2m full scale should be considered in some critical regions where strong shear regions occur near the expected flight path of helicopter main rotors.

In addition, it would help to define appropriate turbulence levels for simulation if power spectra could be obtained down to wavelengths of around 20% of the deck width (about. 2 - 3m full scale). Overall rms data is not sufficient as it requires assumptions about the form of the power spectrum to determine levels of turbulence at wavelengths that affect the behaviour of a helicopter.

8.3 Helicopter modelling

The issues of concern are

- effects from gradients of airflow across the main rotor, particularly gradients in vertical flow
- effects of turbulence
- use of single point or distributed airflow inputs to a helicopter model
- 'ground' effects

8.3.1 Airflow gradients

Gradients of vertical airflow across the rotor can be as much as 30% of the magnitude of the WoD, see Figure 15b. This will produce the same order of forces and moments on the helicopter in 40kn WoD as a typical rotor rolling at about 20°/s. This is likely to generate a significant rolling (or pitching) moment and its importance should be discussed with experts in helicopter flight dynamics. The airflow model contains adequate data to define flow gradients across a rotor either by direct calculations of airflow increments at different parts of the rotor during simulation, or by providing gradient information based on an appropriate rotor diameter as discrete values in addition to the velocity components provided from the current version of the airwake model. Advantages and disadvantages of the two methods of obtaining gradients are discussed in detail later in this section when considering the use of single point or distributed airflow inputs to a helicopter model.

8.3.2 Turbulence

Modelling the response of helicopters to turbulence is a complex subject and there is not yet a consensus on how it should be achieved. It is an essential ingredient in any simulation of helicopter operations in ship airwakes, and it is important to find ways of adequately representing the main effects of turbulence on a pilot's performance of operational tasks. In general terms, pilots are able to respond to turbulence components with frequencies less than about 0.5 - 1Hz and it is turbulence at these frequencies that can cause significant disturbances to the position of a helicopter. Higher frequency turbulence usually has little effect on a helicopter's position but can cause an increase in overall pilot workload. A frequency of 1Hz in 30kn WoD corresponds to a wavelength of about 15m, which is of the same order as the main rotor diameter for many helicopters that operate from small ships. A distance of 15m is also larger than many of the main features such as hangar height, freeboard, and hangar width, that produce turbulence in an airwake. Thus it would be expected that the contribution to turbulence from an airwake will be mainly at high frequency. Disturbances induced as a helicopter moves through the mean steady state airwake may be the main cause of low frequency perturbations.

In these circumstances it seems likely that appropriate turbulence could be generated in an airwake model as a

spectrum of force and moment increments determined from accelerometer measurements on appropriate types of helicopters during actual ship landings in known WoD conditions. It may not be necessary to calculate helicopter responses directly during simulation. Such a random spectrum could be varied with local airflow increments to provide the typical increase in turbulence in regions of disturbed flow. In principle, turbulence is greatest in regions with high shear (velocity gradient) as well as regions where flow increments are large, and it may be desirable to make turbulence intensity a function of both the size of the flow increment and its gradient if evidence from instrumented helicopter operations, and piloted simulation trials, suggests that this further refinement is important.

Some low frequency turbulence will be present when operating in natural wind turbulence outside the more disturbed areas of an airwake. This should be included in flight simulators to avoid an unrepresentative step in workload between natural wind and airwake turbulence.

The appropriateness of using a random spectrum of forces and moments varying with airflow increments could be assessed as soon as some suitable level for these disturbances can be determined from instrumented operations.

8.3.3 Single point or Distributed Airflow Inputs

Most real-time flight simulators calculate aerodynamic forces and moments from airflow conditions at a single point on the aircraft, which is usually the centre of gravity or a nearby reference point. This is very satisfactory for flight in undisturbed air without any airflow gradients. When airflow gradients are present that are significant over distances that are similar to the main dimensions of the aircraft, then it becomes necessary to consider introducing forces and moments due to gradients either by

- defining gradients at the single point and using appropriate derivatives of forces and moments, or
- calculating local forces and moments on different parts of the aircraft and integrating these to obtain total forces.

It is more rigorous to calculate local forces and moments, but it introduces a very significant increase in the scale of computation required to determine aerodynamic forces and moments. It is important to establish whether there are significant advantages in using distributed calculations; otherwise there is no justification (or need) to accept the accompanying large increase in computation requirements in a real-time process.

In the case of helicopter simulation, solid disc or more complex blade element rotor models are both similarly affected in principle by decisions on using point or distributed airflow inputs. However, blade element models require a major increase in computing capability for real-time calculations and this is the only type of helicopter rotor model where local forces and moments can be calculated. Thus it is important to establish whether there will be sufficient differences between using airflow calculations distributed along the rotor blade or using values of the mean airflow at the centre of the rotor and a gradient at the same point.

In general, for real-time simulation there would seem to be little justification for adding the complexity of calculating airflow increments across the rotor, because the forces and moments generated by airflow gradients are likely to be less significant than changes in forces and moments due to the mean airflow and control inputs by the pilot and stabilisation system, and because of some uncertainties about the precision of airflow calculations and the methods used to calculate the effects of non-linear variations of the airflow field.

It is also important to note that gradient information can be used with solid disk models that cannot use distributed airflow data, because only mean disc forces and moments are calculated. Thus it is recommended that helicopter aerodynamic models should be adapted to accept both mean and gradient data from airflow (and turbulence) models.

8.3.4 'Ground' effects

The flow produced by a helicopter's rotor is deflected by nearby surfaces such as the ground or solid vertical walls and affects the local flow at the rotor. During landings over open solid ground the changes in moments and forces induced by recirculating flow are known as ground effect. The presence of parts of a ship will have similar effects, although the flow pattern will be more complex because the surfaces on a ship are of a similar size to the rotor. Only parts of the flow will impinge on particular surfaces depending on the relative position and attitude of the helicopter to those surfaces. These 'ground' effects are a function of the helicopter and the ship. To a first order they can be assumed to be independent of the WoD because velocities in the rotor downwash are much greater than the WoD.

It is important to include the main effects from helicopter downwash to simulate all aspects of ship operations. The adequacy of any representation of 'ground effect' can be assessed by simulating operations in zero WoD.

9. FUTURE DEVELOPMENTS

An empirical modular airwake model that can estimate the airflow in the wake of ships with an aft flight deck for different ship geometries and directions of WoD has been developed and demonstrated in a piloted flight simulator. The model has been compared with results from wind tunnel tests for a ship with an aft flight deck at several WoD directions and shows only small differences.

This is a very promising development and this section describes further stages of development that could lead to the implementation of the model for SHOL

evaluations and test support, and on flight training simulators.

9.1 Model validation and development

Comparison of the airwake model with wind tunnel data has only used test results from a single programme. Wind tunnel data is not totally reliable as an indication of full scale airflow patterns and it is important to compare airwake estimates with full scale data and other boundary layer wind tunnel tests before investing too much further effort in improving the estimating model.

Tests with the airwake model to date have also only been with WoD directions from forward directions round to the starboard beam. It is necessary to validate the model for winds from aft of the beam.

There is thus a need to complete the iterative cycle of validation and model development to demonstrate the suitability of the model to represent airflow for a wide range of ships and all directions of WoD. Some possible improvements to the model have been indicated from the single comparison with wind tunnel data and futher comparisons will show whether these improvements are appropriate or whether they reflect differences that are peculiar to the particular wind tunnel tests.

9.2 Piloted simulation and demonstration

Piloted simulation is another important ingredient in validation, particularly when considering SHOL evaluation and simulated flight training where the views of pilots are an essential part of the process. To date the model has been evaluated on a flight simulator in a controlled, but somewhat artificial condition, with no ship motion or air turbulence. This was very helpful for initial assessments of the model and now that stage has been completed satisfactorily it is important to include airwake modelling together with ship motion and the presence of appropriate air turbulence. This will then represent the usual environment experienced by pilots during operations from ships.

This simulation will depend on the provision of simulation capabilites for ship motion and helicopter response to airwake gradients and turbulence, as well as provision of airwake data including gradients.

The initial model represents sufficient of the main characteristics of an airwake to make it suitable for demonstrating to potential users such as the MoD and Simulator Manufacturers. Such demonstrations will be esential to ensure a smooth and rapid transfer of estimated airwake data into specific flight training simulators, and it would speed this transfer if these demonstrations take place as early as possible.

9.3 Implementation of airwake data on a flight training simulator

The final stage before any routine use of airwake data from this estimating model should be a trial installation and evaluation on a selected helicopter flight training simulator. It will be important to implement all the necessary ship motion, helicopter response and interface modelling on a suitable current helicopter flight simulator and then install a full set of airwake data. This installation process followed by a brief evaluation of simulated operations from a ship will clarify details of the required form of airwake datasets for implementation on training simulators.

10. CONCLUSIONS

An empirical mathematical model has been developed to estimate airflow disturbances around and downstream of the flight deck on any ship with an aft flight deck and for any direction of Wind over Deck (WoD).

Data from the model has been used in an initial assessment on a piloted flight simulator and pilot response has been very favourable. All the major airflow deviations features expected with WoD from ahead, starboard and port 30°, and from the starboard beam were satisfactorily represented. Unfavourable comments were expressed about the lack of turbulence, which is available in the model, but could not be used because the simulated helicopter model at that time did not respond appropriately to simulated turbulence, even in free air. The relatively smooth and gradual transition between conditions in the lee of the hangar and out into free stream was also unrepresentative of actual ship operations.

Piloted simulation demonstrated the significance of regions of static instability where airflow increments increase with distance, particularly for vertical airflow (updraughts or downdraughts). There are tendencies to overcontrol in these unstable airflow regions, and such a region can occur over the deck with WoD from a forward quarter, and wide hangars increase the problem area.

Detailed comparison of data from the airwake model with results from wind tunnel tests on a ship with an aft flight deck show a good comparison in the complex airflow produced with WoD from starboard 30°. Some differences are apparent in comparisons at other WoD directions, which, although sufficient to warrant some further modifications to the airwake model, would not be large enough to influence the pilot's assessment in the simulator.

Development and use of the airwake model has highlighted several points that are important in reducing the effects of airwakes on existing and future ships, providing data for airwake simulation from computer estimates or wind tunnel tests, and simulating helicopter response to airwakes and turbulence. These points are

- Provision of a porous net fence around the edge of the top of the hangar should prevent the formation of vortex flow from the side edges of the hangar for WoD within about 45° from ahead. This vortex provides a significant contribution to undesirable flow velocity gradients near and over the flight deck. Thus eliminating this type of flow

should reduce the effects of the airwake on a helicopter.

- It has been shown that gradients in airwake velocities can produce regions of instability and this means that airflow data must be provided at close spacing to define gradients where they are significant. Spacing of around 1 - 2m full scale is needed in such areas, which is significantly closer than the more normal spacing of about a helicopter rotor radius (about 5m)
- The presence of gradients as large as 30% of the magnitude of the WoD in vertical flow changes across a typical rotor diameter suggests that there will be significant roll or pitch moments generated on a helicopter. Helicopter simulator models need to be modified to respond to such gradients, and it is recommended that airwake models should provide gradient data so that suitable inputs can be provided to both simple disc rotor aerodynamic models and blade element models without undue computing overheads.
- It is noted that helicopter models must include appropriate ground effect simulation to represent the effects of proximity to solid surfaces such as the deck and the vertical face of the hangar.

The empirical airwake model is very promising as an economical and effective means of exploring the effects of ship geometry on Ship/Helicopter Operating Limits, and providing a form of airwake data suitable for use in piloted flight simulators for R & D studies of helicopter operations from ships and for pilot training. Its validity should be tested against a wider range of ship airwake data and the model should be developed to provide datasets for a full range of WoD directions on various ships for use in existing and future helicopter training simulators.

11 REFERENCES

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A dynamic challenge: helicopter/ship interface simulation - development, integration and application

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Summary

Piloted simulation has a potentially major role to play in training, test and evaluation and research in support of the helicopter/ship dynamic interface. The combination of visual/motion cueing and vehicle/environment modelling problems makes the helicopter/ship dynamic interface one of the most challenging in the simulation of aerospace vehicles. The exacting fidelity requirements of this application have hindered the use of simulation in this area until recently. This paper reviews the major fidelity issues of helicopter/ship interface simulation and describes some of the findings of a survey carried out of current simulators to attempt to identify areas that require improvement. The cost and operational benefits of the use of high fidelity piloted simulation in this field are outlined. Current Defence Research Agency (DRA) research work directed at improving models of the natural environment is described, as well as the thrust that future work will take. The uses of the high fidelity helicopter/ship dynamic interface simulation on the DRA Advanced Flight Simulator (AFS) in support of other research packages is described. This work covers the establishment of handling qualities criteria for maritime helicopters and the use of simulation to develop improved pilot visual cues for deck operations. Use of simulation has allowed rapid development at relatively low cost and at much reduced risk.

Introduction

The operation of helicopters from ships, particularly small ships, presents a demanding task for both the aircraft and the pilot. Simulation of rotorcraft is also exacting. It follows that high fidelity piloted simulation of helicopters at the ship interface is a major challenge. Not only is it necessary to simulate the aircraft, but also the vessel and the environmental conditions that affect both. Consequently, although piloted simulation has been used extensively in many fixed wing and rotary wing applications, it has not been in widespread use for the helicopter/ship interface environment.

The DRA at Bedford is currently engaged in an integrated research programme to examine helicopter/ship operations and provide methods of increasing operational limits in respect of more severe sea states, relative wind and visibility conditions. There are three elements to the helicopter/ship work; establishing helicopter handling qualities criteria, developing automatic approach guidance and providing an enhanced cueing environment and improving environment models for use in pilot training simulators. The work has been carried out under three separate, but interdependent and integrated, research programmes. All three rely heavily on piloted simulation as a major research tool and demand improvements in the fidelity of the simulation.

This paper deals with the broad aspects of the uses of helicopter/ship dynamic interface simulation, the key problems faced in improving fidelity and where the DRA effort has been focused. Consideration has also been given to the uses of dynamic interface simulation at DRA, as well as a review of future work in this area.

The requirements of a simulation can differ markedly depending on whether it is to be used for training, development, test and evaluation, or research. Experience at DRA in the research field has been enhanced by collaboration with other countries, notably the US, in understanding the needs for test and evaluation work. Specific research work has also been carried out, as will be described in this paper, to identify the current capabilities and future needs of the training community.

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Benefits of success

The benefits of achieving high fidelity piloted simulation of the helicopter/ship dynamic interface are wide-ranging. There are, as noted above, three key areas that can be supported:

- Research
- Test and evaluation tasks
- Pilot training for ship operations

Obviously, the detailed needs for each of these areas are different, as are the direct benefits. However, in broad terms the benefits are based around the following:

- No need to provide costly aircraft or ships
- Precise, repeatable environmental conditions
- Repeated attempts/replays of particular tasks
- Carry out training and research that would otherwise be difficult, impossible or too risky physically or financially
- Use of simulators as a scratch pad for new ideas
- No flight safety issues

From a research perspective, simulation offers the opportunity to try ideas and concepts without the need for costly and possibly risky flight trials. Indeed, simulation may be the only practical way to carry out some work, such as aircraft control system evaluations. Development can take place using the simulator as a prototyping tool. Concepts can quickly be modified or rejected on the basis of their performance in the simulator.

In the test and evaluation field the drive is to be able to carry out helicopter/ship compatibility testing and evaluate new aircraft, ships or systems against their specifications. Currently, compatibility testing in the UK for one aircraft/ship combination requires an instrumented aircraft and ship for 3-5 weeks and 350 plus deck landings are carried out. This process is vulnerable to weather and serviceability. If the right weather conditions are not found then a restrictive set of operating limits can result. Simulation could be used to clear an initial operating envelope and determine possible critical areas which would then be investigated through flight trials. This would save on the resources required and improve the chances of a good initial operating envelope.

In the training environment there are two areas in which simulation can be beneficial. The first of these is in reducing costs. Provision of aircraft flying hours and ships for training is expensive. The second is in improving the training given to pilots. If students can be taught procedures and how the aircraft will behave, even in the worst expected operational conditions, then pilots who have newly completed training would be more operationally effective. It also means that more effective use can be made of actual sea training time. Currently, there are probably only two or three training simulators in the world that are capable of being used for effective deck operations training.

The effectiveness of the training provided by the simulator will only be fully evident when student pilots move from carrying out simulated deck operations to going to sea with the real aircraft. The true measure of success is the point in the training programme to which pilots can move having completed the simulator training. Ideally, one deck landing in the simulator would equal one in the real world, whatever the conditions. This is not possible with current technology. However, if 10 landings in the real world could be equalled with, say, 14 in the simulator there would still be significant positive training value.

A preliminary worthwhile aim for naval helicopter training simulators would be that, following simulator training, student pilots be able to carry out their first real deck landing sorties at sea, in benign conditions, without intervention from the instructor. Initial procedures and the behaviour of the aircraft at the ship interface would have been effectively demonstrated on the simulator. This baseline capability could then be expanded to include, eventually, the full ship/helicopter operating envelope. In parallel with this, the research and test and evaluation communities should be seeking to produce simulations that will allow some ship/helicopter compatibility testing and research work to be carried out.

Where are the problems

General

Over the last 10 years hundreds of hours of piloted simulation have been expended in the US, Canada and Europe in efforts to revise the handling qualities requirements for battlefield helicopters. In the same time frame very few piloted simulation experiments addressing handling qualities at the helicopter/ship dynamic interface have been reported (references 1 and 2). There has been no significant use of piloted simulation of the dynamic interface in test and evaluation programmes, with the notable exception of the US Navy V-22 programme (reference 3). The 1991 AGARD conference dealing with

aircraft ship operations, although covering many modelling issues, contained no papers concerned directly with piloted simulation (reference 5). This reinforces the fact that adequate modelling is one of the keystones of successful simulation.

Perhaps this lack of dynamic interface simulation usage should not be surprising. Work conducted by the US Navy (reference 1) using the NASA Ames Vertical Motion Simulator (VMS) attempted to define Level 1/2 Cooper-Harper handling qualities rating (HQR) boundaries (reference 5) for all control axes, in various sea states, for a SH-60 class aircraft operating to non-aviation ships. In the event, no Level 1 configuration could be established at or beyond the sea state 3 baseline. The impression given in reference 1 is that the visual cue deficiencies in the VMS (at that time) were a significant influence on pilot handling ratings. This result is entirely consistent with more general findings on research simulators in the mid-1980's. Reference 8 states that for nap-of-the-earth helicopter mission task elements in the early 1980's, pilots typically rated the VMS between 1.5 and 2.5 HQR points worse than in flight; again Level 1 ratings were hard to achieve. By the late 1980's improvements to the VMS visuals, motion system and transport delays had narrowed the gap between flight and ground-based simulation to about 1 HQR point. The work reported in reference 1 is very useful because it demonstrates the significant impact that deficiencies in the simulation can have on the validity of an experiment or in pilot training. It also highlights critical areas where attention must be paid to achieve fidelity when simulating the helicopter/ship dynamic interface - the importance of visual texture and associated depth perception and the degree of realism of ship air wake and turbulence modelling, for example.

It is not an easy task to identify all the shortfalls in state-of-the-art dynamic interface simulation capability. Fidelity of different components must be kept in balance with each other. For example, a highly capable ship air wake and turbulence model may require the use of a comprehensive aeroelastic blade element model for the main rotor to be fully effective. Inter-relations such as these require careful consideration before committing to expensive research and development work.

The DRA conducted a survey of a number of dynamic interface simulators (reference 7). The aim of the survey was to assist in indicating where the primary deficiencies lay in providing an adequate simulation of the helicopter/ship dynamic interface, and then redirect research effort if necessary. The simulators surveyed were mainly training devices, but the V-22 simulation on the US Navy Manned Flight Simulator (MFS) was included. The ages, and consequently technologies, of the training devices ranged from 1979 to 1991. The survey was limited in its objectives and in the information that it could provide. However, it gave insight into the views of operators and their perceptions of the devices with which they work. These insights are summarised below under various headings.

As part of the process of assessing what is currently possible, the DRA also recently carried out an evaluation of the latest high fidelity pilot training device to come into use. This was the US Coast Guard HH-60J Jayhawk facility, which began to be used for pilot training at the end of 1994. This was invaluable (reference 8). The specification for this device determined that no untried technology should be incorporated. Consequently, much effort was expended on refining available technology and achieving good integration. This was a successful approach. Good cueing, special attention to scene content issues, and the fact that a specially instrumented aircraft was used to collect data for the aircraft model has produced a simulator with the ability to be used for some deck operations training. This evaluation demonstrated what is possible with 1990 technology.

Validation of a simulation is always difficult, and is a key area of concern. However, the ship environment has particular features that cause problems. The environment around the flight deck of a ship is difficult to quantify. For example, taking wind or turbulence measurements down the final approach path would be very difficult. The air wake environment over the flight deck can be captured to some degree, but not the effect the aircraft has on it as it is inserted in the flow field. Validation is a key issue that will require more attention.

Visual system

The tasks that are to be performed using the simulator have a strong impact on the specification of the visual system. For deck operations the pilot faces problems which are peculiar to this environment:

- Cues can be very limited, particularly at night
- In degraded visual conditions the ship itself may provide the only closure rate and positioning cues
- Pilots use the sea surface to assist in estimating drift and to predict ship motion

This means that scene content, peripheral cueing, and adequate modelling of the sea surface are all of particular importance.

Simulators with modern display systems provide adequate fields of view (typically 200 degrees in azimuth, biased to the right hand seat, and at least 40 degrees in

elevation). A primary concern is the lack of downward field of view to the right for conducting precision hovering alongside and over the flight deck and for the landing task. The field of view issue is one which can largely be solved by providing a state-of-the-art image generation and display system. For an adequate field of view to be achieved (past the beam position on the pilot's side of the aircraft and downwards at least 35 degrees) there are several options; using a wide display, a motion-mounted dome, area of interest displays, or by employing helmet-mounted visuals. All of these have advantages and disadvantages ranging from cost to added weight on the motion system - which also comes down to a cost issue.

Lack of scene detail was the most frequently noted problem with image systems. Lack of texturing and inadequate resolution were also noted as difficulties. Phototexturing can make a large positive impact on scene content and the number of polygons available per image channel continues to rise. One principal requirement for deck operations was for visual modelling of the sea surface to accurately reflect the actual sea state.

Motion system

Many current simulators lack performance in cueing for low speed manoeuvres, particularly in the heave axis. Significantly, when operating at night, or in degraded visual conditions, pilots become more reliant on accurate motion cueing to be able to complete the task successfully in the simulator. As much of the dynamic interface simulation requirement lies in these types of operations, adequate motion cueing is crucial.

Tests have indicated that the removal of motion cueing will have little effect on task performance in moderately demanding tasks. However, the pilot's workload in achieving that performance increases markedly. This indicates that, without motion cueing, a pilot will exhaust his spare capacity at an earlier point (reference 9). Vibration can also be a significant cue to the pilot.

Most current simulators use a standard six-degree of freedom motion platform. Generally, the motion systems are used for all flight tasks, although motion sickness of some users was noted. Motion cueing was considered to be adequate, although heave cues were identified as a weak area.

An interesting result from the survey was that some users considered that the primary task of motion cueing is to reduce the effects of motion sickness. It was felt that few had a real grasp of the significance of motion cueing in assisting the pilot to adopt the correct control strategy for a particular task.

Aircraft mathematical model

None of the simulators surveyed were considered by their operators faithfully to reproduce the handling qualities of the real aircraft. This had led to a number of problems in use of the devices for particular tasks. For deck operation simulation to be meaningful it will be necessary to employ models able to react accurately to ship air wake and turbulence, as well as possibly having some main rotor/tail rotor interaction capability. There is no doubt that many current simulators suffer from a lack of adequate aircraft data for the model. Traditionally, in the UK, data packages have been the responsibility of the simulator manufacturer and this has lead to poor or inadequate data being used in modelling work. The US Navy sets standards for data packages that it requires from the prime contractor of the system being procured (reference 10). This method ensures that sufficient and relevant data for modelling requirements is available.

Ship air wake and turbulence modelling

Ship air wake and turbulence modelling plays a major role in performing deck operations. Until recently, little attention was given to the provision of realistic air wake and turbulence models. This was because other deficiencies, such as the visual system, meant that deck operations could not be conducted effectively in a simulator. The position of the flight deck and the close proximity of superstructure means a turbulent environment with many updraughts, downdraughts and vortices. These impinge on the aircraft causing both low and high frequency effects for which the pilot has to compensate, so increasing workload and influencing pilot control strategy. The relative wind speed and direction around the flight deck and superstructure decides the degree of disturbance. An additional consideration is the effect of hot gases from the ships exhausts.

Most current simulators have crude, random, air wake and turbulence modelling. Probably the best model currently available is that developed by the US Navy and in use on the V-22 simulation in the MFS (reference 11). A version of this model is used in the US Coast Guard HH-60J simulator. A key issue with these turbulence models is the way in which they are applied to the aircraft. In all cases this was through the aircraft centre of gravity. More complex models would require a more effective interface with the aircraft.

A major question concerns the fidelity of simulation required. From the training effectiveness standpoint the level of fidelity will depend on the level of training required. The number of different cases (ie combinations of ship types with relative wind strength and direction) that are required to be simulated can

become large. Test and evaluation uses may require the generation of a large number of cases for ship/aircraft compatibility testing.

Ship motion modelling

Ship motion also plays an important part in the launch and recovery tasks. Pilots must take-off and land inside the determined limits for the aircraft. In a simulator this means that a realistic presentation is important. The wind direction and speed, the direction that the sea is running and the speed of the ship are all significant factors. As with air wake and turbulence effects, this area has received little specific attention as deck landing was not part of the usual suite of tasks for naval rotary wing training simulators.

Most current simulators either provide simple harmonic motion driven models or crude models using a small number of superimposed sine waves. Behaviour representing several ship types is generally available. These models are generally not suitable for conducting any form of realistic training. This is due to the complex nature of the wave environment (reference 12) and to the fact that the environments that the ship operates in can vary markedly.

With ship motion modelling, as with turbulence modelling, a significant question concerns the variety of conditions to be simulated. A small number of cases lends itself to time histories stored in memory and replayed as required, given that the data is scalable over a significant number of sea states. Large numbers of ship types and cases would dictate the need for some form of on-line modelling.

Current DRA research

Current DRA research in the dynamic interface area is concentrated on three topics; ship air wake and turbulence modelling, ship motion modelling, and a continuing assessment of what is being achieved by state-of-the-art training simulators - this allows constant review of research objectives. In hand with this work there are other research activities in progress that will benefit the programme directly or indirectly. These include aircraft mathematical modelling activities and work on helicopter motion cueing.

Ship air wake and turbulence modelling

General

This is a large subject and it is receiving much attention in the DRA and other nations. A recent literature survey carried out by the Institute of Aerospace Research of the National Research Council of Canada (reference 13) listed many source papers on the subject. Many of the papers referenced in this paper contain large reference lists themselves.

DRA air wake modelling work

The aim of the DRA work has been to develop a generic model of the flow environment over and around the flight deck of a frigate-sized ship, suitable for use in piloted simulations. The model is related to certain characteristic features of the ship's geometry in order that different ship types can be represented. The details of the work have been reported at reference 14 and this work should be consulted for the technical detail of the research. A brief outline is given below.

The wind blowing over the flight deck and superstructure of a ship induces a complex three-dimensional flow. The solution adopted in the DRA model has been to identify basic flow types and perform off-line calculations to produce a suitable three-dimensional wind field. The basic flow types include:

- Corner flow - the flow towards and around a corner when the approaching flow is directed mainly towards a steep face
- Lee rotor - a horseshoe vortex that forms in the lee of a bluff body (figure 1)
- Edge vortex - corners of objects at a shallow angle to the incident wind over deck will generate a vortex starting at the upwind corner and growing as it moves downwind (figure 2)
- Profile drag - an object in a wind stream causes a reduction in momentum in its wake
- Inflow - necessary to 'balance the books' and ensure that there is no air flow through any aft-facing solid surface such as the hangar end

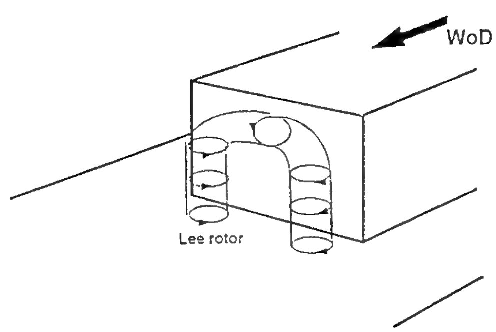


Figure 1 - Lee rotor

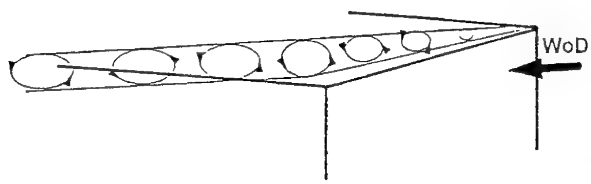


Figure 2 - Edge vortex

Each of these flow types has a characteristic form determined by the speed and direction of the incident air flow and the geometry of the ship and its superstructure. The dominant flow type will change with wind direction. Knowledge of the fundamental behaviour of flow round bluff bodies has been combined with data from wind tunnel tests (references 15 and 16) and with flow visualisations recorded on video to set overall dimensions, in both extent and strength, of each flow type. Contributions from each type have then been combined in a linear manner and with suitable blending to achieve the desired results. With further information, perhaps from full-scale measurements, it would be possible to adjust the contribution of each of the constituent flow types.

The aircraft is strongly affected by the variations in local wind with helicopter position, rather than the absolute value. Furthermore, as the presence of the ship will change the local wind flow, the model is expressed solely in terms of incremental velocity vectors which, when scaled by and added to the datum wind over deck, give the total local wind components.

A simplified ship geometry has been assumed, in which the rear portion of the hull has a flat flight deck and a near-rectangular hangar. Provision is made for fence structures on top of the hangar and for the slightly obtuse angles used between surfaces to reduce radar reflections. The model is designed primarily to provide appropriate flow conditions for positions aft of the hangar face. Forward of this, the superstructure becomes more complex. Flow in this region is represented only approximately, to ensure that there are no unrealistic disturbances as the helicopter flies through. Specific geometric parameters are used appropriate to the ship in use.

For a given wind direction, appropriate flow elements are selected and combined. The results are expressed as a table of wind vector components in three dimensions. The position of the helicopter relative to the flight deck is input to the model, normalised by a characteristic length given by the ship's beam. Output from the air wake model is expressed as a spatial distribution of three non-dimensional incremental components of the wind speed along, across and normal to the fore/aft axis of the ship. These increments are independent of actual wind speed and are scaled by the wind over deck, or more strictly by the datum wind over deck obtained by combining vectorially the free stream wind speed with the ship's speed.

The vehicle model used for the trials was the DRA Helisim model (reference 17), configured as a Lynx helicopter with full automatic flight control system. Helisim defines a generic non-linear helicopter mathematical model with the main rotor represented as a disc. Disturbances due to winds and turbulence are fed to the model in three axes through the aircraft centre of gravity. The resulting forces are then transferred to the rotor hub within the model.

Eight relative wind cases have been generated to date, with four wind directions and two wind speed cases provided. Figure 3a shows the flow vectors at a point one ship beam width to port of the hangar centre-line for a relative wind case of 30 degrees on the starboard bow (green 30). Figure 3b shows the same wind case in the cross-deck plane at 1.1 beam widths aft of the hangar face, approximately the position of the rotor hub during landing. These figures clearly show the changes in mean flow velocity that the aircraft will encounter around and over the flight deck.

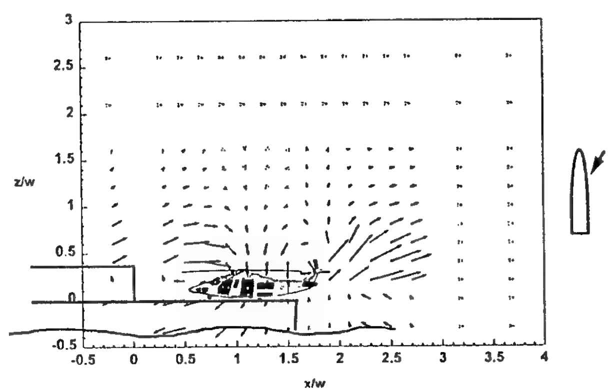


Figure 3a - Vector plot of wind variation, fore/aft view

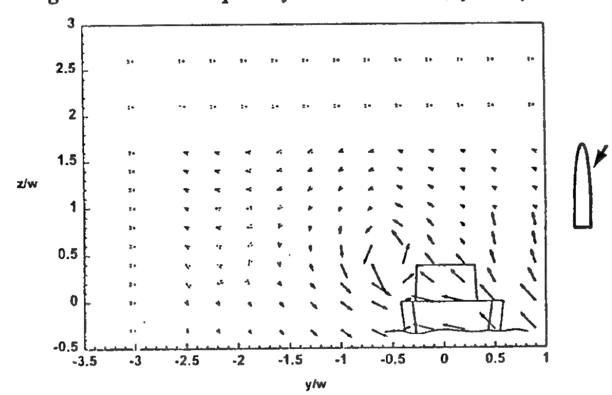


Figure 3b - Vector plot of wind variation, lateral

The model performed well in tests, with the aircraft experiencing the gross, low frequency effects that the pilot expected (reference 18). These included updraughts generated by the up-wind flight deck edge, masking effects in the lee of the superstructure and the downdraught experienced from the roof of the hangar during the descent to land. Evaluation pilots have commented that effects were representative of the real world, producing correspondent increases in pilot workload. This has demonstrated that the concept of this model is valid and should be developed further.

The DRA model currently suffers from a lack of appropriate turbulence modelling. The current turbulence model in use on the AFS was originally derived for fixed wing work. In trials with the air wake model it was very ineffective in producing appropriate reactions of the aircraft. It is unclear whether this was due to problems with the turbulence model itself, or with the reaction of the aircraft mathematical model. Work is under way to attempt to define the problem and produce a new or revised model, as appropriate, for demonstration on the AFS in 1996.

This research work concentrated on a proof of concept, generic approach. Further work will be required to investigate whether specific data will be required for particular ship types. Certainly, in the training environment it is likely that, unless a vessel has particular features that produce unusual flow patterns, a generic model may suit several similar ship types. However, little work has been conducted in this area. One study (reference 19) indicated significant differences between a generic model and air wake tests carried out at sea on an a real vessel. For ship compatibility testing more type-specific work would be required with detail data for particular ship type being made available. Indeed, there has recently been an approach from UK MoD to carry out such a helicopter/ship air wake and turbulence assessment to assist in ship design work for a new class of vessel. The aim of the work would have been to attempt to reduce aircraft operating difficulties due to the effects of ship air wake and turbulence. Unfortunately, the technology is not yet mature enough to reduce the risks of taking on such work to a sufficient level. However, it is likely that this type of work will be undertaken in future by the DRA using the AFS.

Wind data

Wind tunnel testing can be an expensive way of gathering the necessary data for inclusion in these models. There are alternative methods of generating the necessary information. One would be to conduct testing at sea on actual ships. Some countries have used an instrumented mast mounted on the flight deck for this purpose (reference 20). However, results have been questionable and ship time is very expensive. A version of the air wake model may be developed in the future to conduct an AFS assessment of data collected using US equipment on a UK frigate. Laser anemometers could be used, which can gather data way from the flight deck and more rapidly than an instrumented mast. Computational fluid dynamics may be another method, as has been used by the US Navy (reference 21).

Other considerations

None of the models currently in use take account of the effects of ship motion on the air wake and turbulence flow fields. In high sea states the motion of the superstructure will cause distortions in the flow. However, currently it is not even clear whether the effects of ship motion are significant. Some work has been carried out that may indicate the levels of influence (reference 22), but further work will be required to adequately define the problem.

Both the US and UK models use large amounts of data in look-up tables to represent the steady state flow field. While this may be acceptable if only a limited number of cases are needed problems may arise with on-line data storage if larger numbers of cases are required.

Evaluations on the AFS have indicated that aircraft cues other than the pure reaction of the aircraft are important in simulating air wake and turbulence effects. The cues provided by vibration of the aircraft were noted as being conspicuous by their absence. These effects could include reaction of the main and tail rotors to vortices passing through them and to the influences of main rotor/tail rotor interactions. These findings have prompted work in this area to be included in the future DRA programme.

Future DRA work

The future programme dealing with ship air wake and turbulence modelling at DRA plans to:

- Integrate the model with an aeroelastic blade element aircraft model (in 1995).
- Develop more relative wind speed and direction cases (up from the current 8).
- Examine the possible use of real ship data gathered at sea to provide the steady state flow pattern.
- Develop and integrate an improved, or if necessary, new turbulence model, depending on the findings of work to be carried out this year.

The work on turbulence will be assisted by a flight trial using a heavily instrumented Lynx helicopter (the DRA's ALYCAT Lynx, ZD559) to investigate the reaction of the aircraft in flows behind bluff structures. The trial will also record pilot control strategies and reactions in flight in these regions. Current plans call for a number of wind cases to be evaluated. A simulated ship environment will be created by use of containers assembled on an airfield to represent the approximate dimensions of a frigate flight deck and hangar. The aircraft is equipped with a full suite of instrumentation including pressure and strain-gauge fitted main rotor blades. The results from this work will be applied to the air wake, turbulence and aircraft mathematical modelling programmes.

An area not currently being addressed in the DRA simulator programmes is that of the influence of the ships hot gas exhausts on the aircraft. There are currently no plans in the DRA programme to address this, but some work that may be of future use is being undertaken in the US. Again, the aircraft simulation community is faced with not being able to quantify the extent of the influences of a particular feature on the fidelity of the simulation or the difficulty of the piloting task.

The provision of on-line real-time models, as available for ship motion modelling, would be a desirable aim. Once validated, these models would not require the collection or generation of the necessary steady flow and turbulence data. However, developing such models, with sufficient fidelity, and in real time, is some way in the future, if it were to be possible in a cost-effective manner at all. The technical challenges and cost of the necessary computing power may see this remain an unobtainable goal.

Validation is always going to be a difficult issue with the air wake and turbulence work. One suggested course would be to fly a fully instrumented aircraft to a ship in trials at sea. The same runs would then be performed in the simulator using an aircraft model configured appropriately and with all other models set up to provide the conditions found at sea. All other considerations aside, the pilot control strategy and the reaction of the aircraft could then be compared with those found in the flight trial. However, this would be an expensive exercise and the results, due to other simulation limitations if nothing else, would likely be ambiguous. Validation questions remain to be adequately addressed. Another problem that none of the current modelling work addresses is the influence on the flow field generated by the insertion of the aircraft, and in particular the main rotor. Distortions are bound to occur - but are they significant? Questions such as these remain to be addressed.

Ship motion modelling

General

As with ship air wake and turbulence effects, ship motion is a key task driver in the ability of the pilot to carry out a successful launch or recovery. Ship motion is principally dependant on the sea state and the hull form of the ship (reference 12). 'Sea state' includes such parameters as wave direction, significant wave height and other dynamic characteristics such as modal period and will be influenced by the sea area being traversed and the season of the year. The way the ship responds to seas will be governed by the natural behaviour of the vessel and by such variables as ship speed and heading with respect to the waves.

A 'real wave' environment can be complex because it can consist of a long wavelength swell, induced by a wind that has been blowing several hundred kilometres away, in combination with a locally generated wave system induced by the local wind. The underlying direction of movement of each main component can be quite unrelated.

Although a wave environment may have been generated by a complex set of events, waves at a given point and a given time can appear to be like a series of superimposed sine waves. The resulting ship motion has a similar sinusoidal appearance (see figure 4). Some of the key properties of ship motion, which a simulation should reproduce, are the characteristic amplitudes of movement, the frequency content and the appearance of lulls when the ship experiences a period of low motion activity. It is these lulls, or quiescent periods, that provide opportunities for the pilot to launch or recover the aircraft. Consequently, it is important that they appear in any simulation of ship motion.

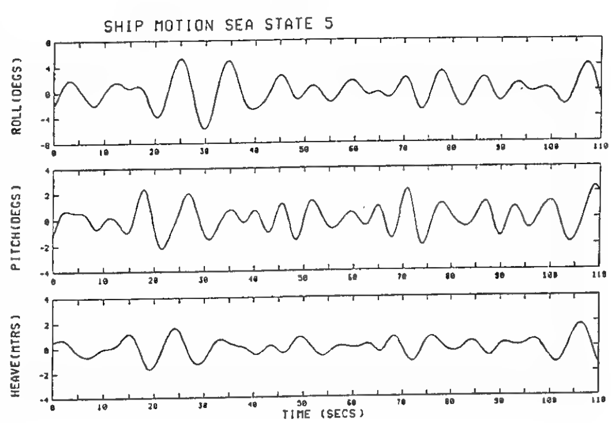


Figure 4 - Example of typical ship motion trace

There are two methods of providing a representation of ship motion:

- By use of an on-line real time computer model
- Employment of time history data

The latter method is practicable as long as a large number of cases are not required. DRA work has used time history data, produced using a non-real time computer model, replayed in real time for simulator trials. A number of cases were generated and these can be used depending on the needs of a particular trial. The data is produced for sea state 5.5, but can be scaled between sea states 4 and 7, as the basic characteristics of the wave forms remain the same over this range. However, only one case is stored for use at any one time. The data covers 20 minutes of motion which at the end replays via a smoothed loop. The start point of the data is varied for every run carried out during a simulation sortie so that the pilot does not become familiar with a particular portion of the data. Data provides ship's roll, pitch, heave, yaw and sway axes.

The DRA currently holds samples of data for all Royal Navy aviation-capable ships. This method is attractive because it provides an easy solution. The major limitation is that a large spread of cases would require a significant amount of memory storage space. With a simulation sample rate of 50 times per second and assuming a 20 minute time history is the minimum acceptable, then 60000 data points would be required for each axis. This is a lot of data. It may not be necessary to sample the time history at the full data rate of 50 times per second. Linear interpolation techniques may allow a lower sample rate, of perhaps 10 times per second. However, this has yet to be evaluated on the simulator. Pilot acceptance of the current method of representing ship motion on the AFS has been high. No adverse comments on ship motion have been recorded and, whilst there has been little unprompted praise, this usually indicates that the simulation is adequate for the task being performed.

It would also be possible to use real ship time history data. This would probably only be required for specific applications, but could be useful. Real data is available in limited quantities for a few conditions and could be used if necessary. The same problems apply with the use of this data as with computer-generated data in terms of flexibility, storage space and a limited number of available conditions.

On-line, real time models have been implemented by other research simulators and for some training devices. Generally these models employ many sine waves superimposed to provide the necessary motions. These models can be configured for particular ship types. The models in use on the MFS and HH-60J simulators have been viewed and appeared to produce good results. These models use 16 sine-waves, although current non real-time models can use up to 40.

It is intended to fully evaluate the US Navy ship motion model on the AFS during 1995. An evaluation will then be made of the level of fidelity of the model and its suitability for particular tasks.

Aircraft mathematical models

As with other aspects of simulation discussed here, the field of aircraft mathematical modelling of helicopters is undergoing constant evolution. Many of the new features becoming available are not revolutionary. It is the ready availability of faster and cheaper computing power that is allowing more complex models to be run in real time. There are many features that are, or soon will be, available with current technology:

- An individual blade element model for the rotor. This would include modelling of flapping dynamics and lead/lag, torsion and rotor speed effects. Stall and Mach effects could also be incorporated.
- Incorporation of forces and moments acting on the fuselage, fin and tailplane for an appropriate range of pitch and sideslip incidence. Modelling of rotor wake effects will be possible in the near future.
- Blade element tail rotor modelling should soon be available, as will main rotor/tail rotor interaction effects. These have an important bearing on the operational envelope of some helicopters.

As noted above, DRA efforts include running the current air wake and new or improved turbulence models with an aeroelastic blade element main rotor model this year.

As has been suggested, the aircraft mathematical model has a profound influence on the effectiveness of the simulation of air wake ad turbulence effects. Currently, the outputs of models are generally applied either at the aircraft centre of gravity or at the main rotor hub. As the aircraft models become more complex and of higher fidelity air wake and turbulence models will need to evolve to utilise the additional fidelity available. Having the aircraft model react to the other models at several key points on the fuselage, as well as across the main rotor may be appropriate. Inclusion of the tail rotor, and the reactions between main and tail rotors will also be a consideration.

Visual cues

Achieving adequate visual cueing for the helicopter/ship interface environment requires a high performance visual system. To achieve meaningful simulation of deck operations the visual system will become a major cost driver of the device. Research into this area for the dynamic interface will begin this year. The aim of the research will be to identify the key elements of visual modelling on which effort should be concentrated when modelling a vessel.

What is known is that a large field of view is required, both to provide the pilot with a sufficient view of the vessel, but also to maintain adequate levels of peripheral cueing. A high scene content is also important. The level of cueing provided by a vessel at sea is somewhat less than might be available in a confined area on land. Consequently the pilot has to rely on a limited number of cues to stabilise and position the aircraft over the flight deck. The sea surface also provides the pilot with cues as to height and ship motion.

Currently, a phototextured Type 23 frigate model is used on the AFS (figure 5). This visual scene has been displayed on three cockpit monitors giving a azimuth field of view of 120 degrees and a maximum of 48 degrees in elevation. This has proved to be limiting in some respects due to the lack of azimuth cover to the right and downward field of view to the right. Pilots have had to compensate for these deficiencies by modifying the way they carry out the landing task. Obviously, this is not desirable. Enhancements to the visual system will be in place soon that will increase the azimuth field of view to 210 degrees and the elevation field of view to the right to 66 degrees. These improvements should have a significant positive impact on the level of cueing available on the AFS.

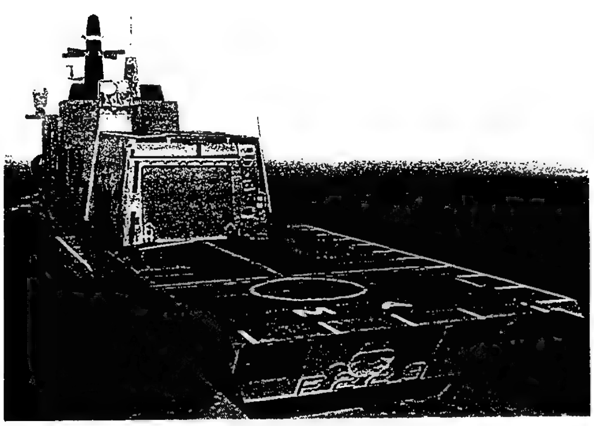


Figure 5 - AFS visual model of Type 23 frigate

In terms of scene content, phototexturing can provide improved cueing. Although providing more 'realism' to the picture and assisting in providing positioning information, phototexturing is not the whole answer. Individual modelling of key features on the flight deck and superstructure is still necessary. Modelling of a dynamic sea surface is also a highly desirable feature. Without this the picture can seem very artificial in even moderate sea states. The ship has motion, but the sea surface remains flat. In higher sea states, height cueing can become difficult. Accurate modelling of ship-mounted visual aids is also essential for training devices.

Research at DRA Bedford is concentrating on scene content issues at this stage. There are plans to conduct eye-tracking experiments, both in the simulator and during ship trials, to identify the key features the pilot uses during the final approach and landing tasks. Some work on pilot eye movements during deck landings was carried out by the Department of National Defence of Canada some years ago in support of visual aids work (reference 23). This showed that pilots concentrate on very specific areas of the ship superstructure during the landing task. If these are identified for Royal Navy ships it should be possible to concentrate modelling efforts on these areas and so improve the level of realistic cueing.

Motion cueing

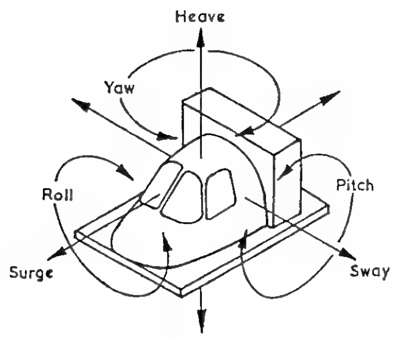
Motion cueing is an important element of high fidelity helicopter simulator. The level of motion cueing has an impact on the workload the pilot experiences in attempting to carry out a task to a particular performance requirement. No helicopter/ship interface specific research work is being conducted at present. However, other work carried out by the DRA (reference 9) has indicated the benefits of dynamic seats to provide additional, and in particular, heave cues. Further trials evaluating the use of a multi-axis dynamic seat for helicopter tasks will take place this year using the AFS.

Use of the AFS for dynamic interface research

General

The AFS at DRA Bedford provides a high fidelity general purpose research tool with a high degree of flexibility to enable tailoring for a wide range of fixed and rotary wing applications. The simulator can be configured to the needs of a particular task by selecting hardware and software options. The key facilities include motion and visual systems, cockpit modules, pilot controls and primary flight instrumentation. These are complimented by the capability to build software models of the aircraft, its systems and the natural environment in which it is operating. The facility's foremost asset is the

Large Motion System which provides a unique and highly capable motion cueing system (figure 6). Notably, the high displacements, velocities and accelerations shown can be achieved simultaneously in all five axes. More details can be found in reference 24.



PERFORMANCE ENVELOPE

Axis	Displacement	Velocity	Acceleration
Pitch	± 0.5 Rad	± 0.5 Rad/s	± 2 Rad/s^2
Roll	0.5 Rad	1.0 Rad/s	3 Rad/s^2
Yaw	0.5 Rad	0.5 Rad/s	1.5 Rad/s^2
Sway (Surge)	4m	2.5 m/s	5m/s^2(0.5g)
Heave	5m	3 m/s	10m/s^2(1.0g)

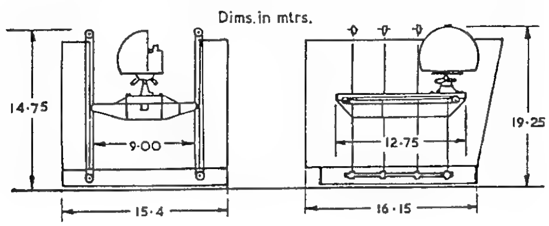


Figure 6 - DRA AFS Large Motion System

Two areas are being studied: handling qualities for helicopters involved in ship operations and pilot visual cueing aids for ship operations.

The task

All tasks were assessed using, as much as possible, the same test and assessment methodologies. This assisted in being able to compare results, as well as providing pilots with continuity and reducing the overheads in running trials.

Task design was based on a mission task element (MTE) concept promoted in combat helicopter flying qualities research, using the methodology of the US Army Aeronautical Design Standard 33 (ADS-33) (reference 25). This is the generally accepted methodology for military helicopter handling qualities. A MTE represents a discrete task, representative of a realistic mission phase with defined initial and terminal conditions. The mission phase under investigation in these trials was the Royal Navy deck approach and landing profile. This meant placing the aircraft on a 3 degree glide slope and a 165 degree radial from the port bow. Pilots were instructed to fly a standard approach to the 'port wait' position. At this point the aircraft is brought to a hover alongside the flight deck where the main rotor should be clear of the ships side and the aircraft in the correct fore/aft position. The aircraft is then held in this position until a suitable quiescent period in ship motion is identified. The aircraft is then manoeuvred over the landing point and a landing made when the pilot is satisfied with positioning and deck motion.

For assessment purposes this profile was divided into two MTEs, as follows:

a. Approach to and maintenance of a steady hover alongside the flight deck.

b. Sidestep manoeuvre, positioning over the flight deck and landing.

In the simulator the task was altered by presenting the pilot with various combinations of night and day visual conditions and using different sea states.

Assessment

Success in completing the task was measured not only against the pilot perception of his performance, but also by setting task performance parameters. These parameters were monitored and recorded and, in the simulator, were available to the pilot during debriefing. The parameters were structured to reflect the Cooper-Harper handling qualities rating (HQR) scale (figure 7 and reference 5) for pilot subjective assessment. Consequently, task performance was divided into bands of 'desired' (Level 1), 'adequate' (Level 2) and 'unacceptable' (Level 3). These ratings were included in a post-run debrief questionnaire. This was backed by a post-sortie questionnaire. Task performance parameters included accuracy of landing and vertical velocity at touchdown, time spent in the hover over the flight deck and the number and severity of overtorques.

Handling qualities

The handling qualities work (reference 2) aims to establish handling qualities criteria for the operation of helicopters from ships. This will provide the MoD with a comprehensive document to assist in the specification and assessment of future maritime rotorcraft, maintaining MoD's 'intelligent customer' status. The work is looking at the full range of control response types as well as the impact of key control parameters. These parameters include roll and pitch bandwidths, control powers and the influence of vertical damping and thrust

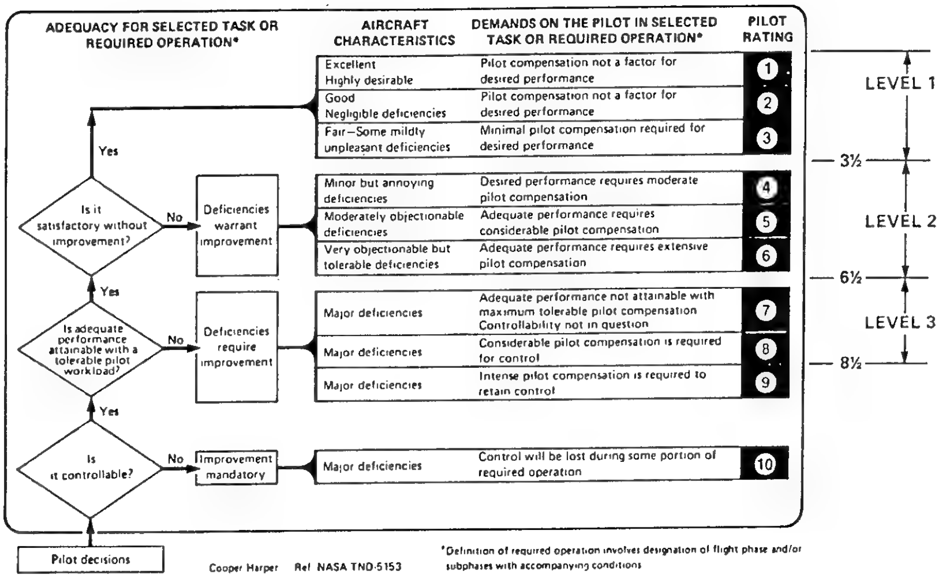


Figure 7 - Cooper-Harper handling qualities rating scale

margin on task performance. Other features being investigated include:

- The impact of integrating controls and displays by providing piloting information on a helmet-mounted display
- Investigation of the use of trim systems
- The impact on task performance of limit protection systems
- The influence of providing a limited authority carefree handling system to allow the pilot to more fully utilise the performance of the vehicle

The work has involved the use of the DRA Conceptual Simulation Model (described in reference 22 and 26). This model was originally developed to permit the exploration of helicopter handling qualities in a systematic fashion. Characteristics in any axis can be changed without impact on the response in other axes and cross-coupling can be entirely eliminated if required. Response types can be selected and a wide variety of parameters can be altered to assess their impact on handling qualities.

Work so far has concentrated on large helicopter operations from small ships. Roll and pitch bandwidth were altered, together with control power, using sea state to vary task difficulty. Heave axis evaluations have used damping and thrust margin as the variables, again using sea state to vary task difficulty. The impact of providing the pilot with an audio torque warning has also been investigated.

Figure 8 shows the landing scatter for two of the roll/pitch bandwidth configurations trialled. A tighter lateral pattern is evident for the higher bandwidth case, as would be expected. Up to a point, higher bandwidth provides more precise control and allows the pilot to improve task performance. Pilots were consistently concerned about fore/aft cueing and this is reflected in the results. The large fore/aft spread is probably due to deficiencies in peripheral cueing and the pilot not being able to see the deck edge. Although this was recognised as a limitation in the simulator, fore/aft positioning is also a major concern in the real world.

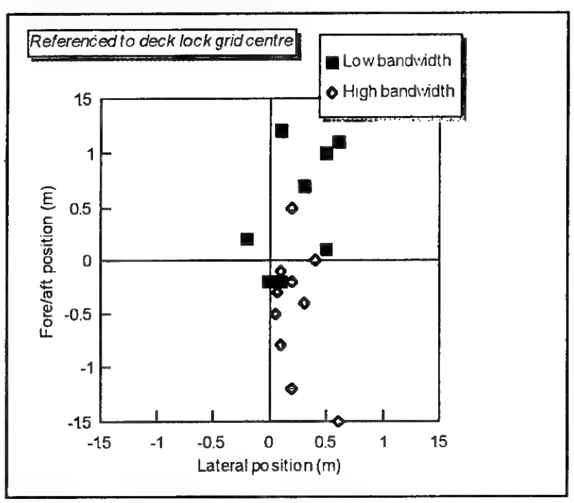


Figure 8 - Landing scatter comparison for high and low bandwidth pitch and roll configurations

The pilot ratings returned for the landing task for roll bandwidth are shown in figure 9. The results clearly show that, although Level 1 performance was possible at

the higher bandwidths tested, this was only possible in sea states up to three. From the results it could be hypothesised that an increase in bandwidth to 3.5 rad/sec would give Level 1 performance in sea states up to five.

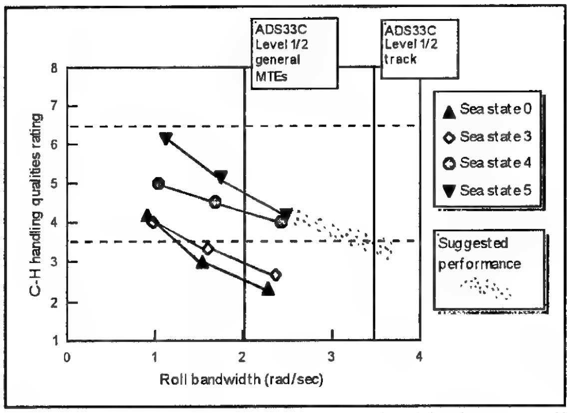


Figure 9 - Mean HQRs for roll bandwidth showing all configurations and sea states

The results have clearly shown that the landing task is the critical mission task element. There are also indications that the landing task closely corresponds to the ADS-33 Level 1/Level 2 boundary for a task with a significant tracking element. It also indicates that, particularly for the vertical axis, specific ship operation mission task elements and task performance parameters are required. These initial results suggest that the ADS-33 Level 1/Level 2 boundaries need modification for helicopter/ship operations.

Visual aids

Current visual cueing aids on small ships of the Royal Navy were generally developed in the early days of helicopter operations with small helicopters and there has been little evolution over the years. The introduction of larger aircraft for small ship operations, such as the Sea King and, in the not too distant future, the EH101 Merlin, have highlighted the shortcomings in visual cueing during the final part of the approach to the ship and over the flight deck, particularly when conditions are poor. If full benefit is to be drawn from the investment in the highly capable Merlin, then improved pilot visual cues for ship operations will be necessary. The visual aids work has investigated how to provide these improved pilot visual cues through developing patterns of electro-luminescent panels in place of traditional white floodlighting. These panels can be placed around the flight deck and superstructure and provide the pilot with familiar patterns (figure 10). Geometric positioning aids have also been developed to assist the pilot in positioning the aircraft more accurately over the flight deck. In hand with this, work has also been carried out to develop an indication system which shows the position of the aircraft deck lock probe relative to the centre of the ship deck lock grid (figure 11). The simulator has been used not only to develop display formats, but also to develop strategies for use of the device. This work is covered in reference 27.

For this work the simulator has been used as a versatile and easily changed system to try out new ideas, modify them or reject them. It is then used as a development aid

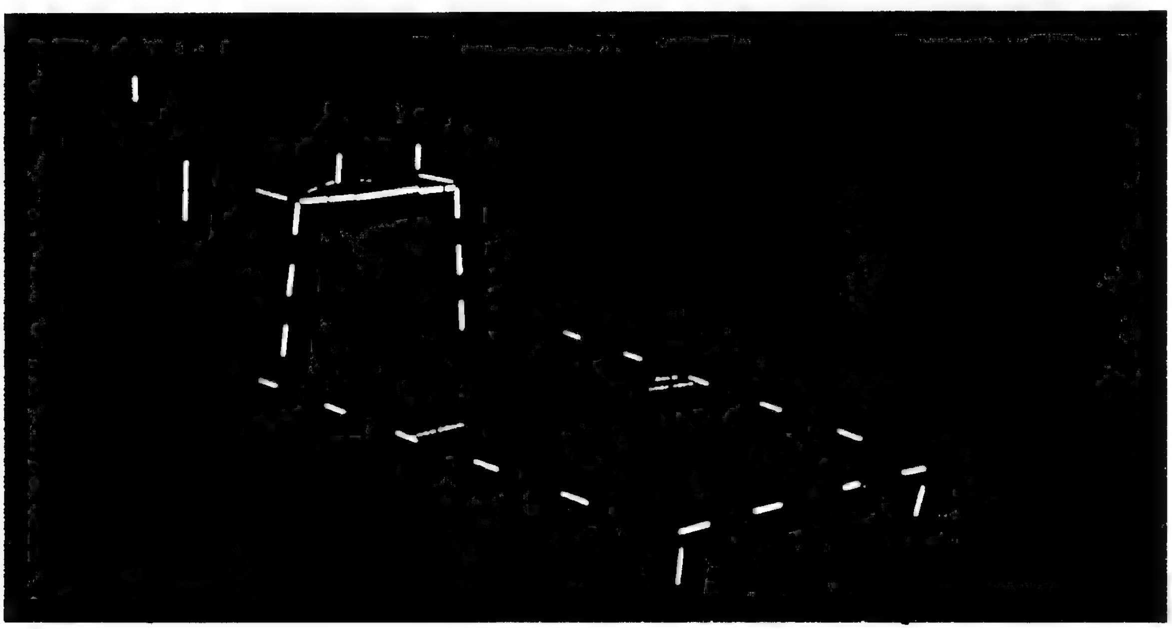


Figure 10 - ELP pattern shown installed on Type 23 frigate during ship trials

aid to move concepts forward towards flight trials. Finally, the simulator can be used in direct support of flight trials and as something of a training aid so that pilots know what to expect when flying to a real ship with these aids for the first time. Without the simulator the development of solutions would have taken longer and involved considerably more financial and physical risk. There is no doubt that it would also have been more expensive.

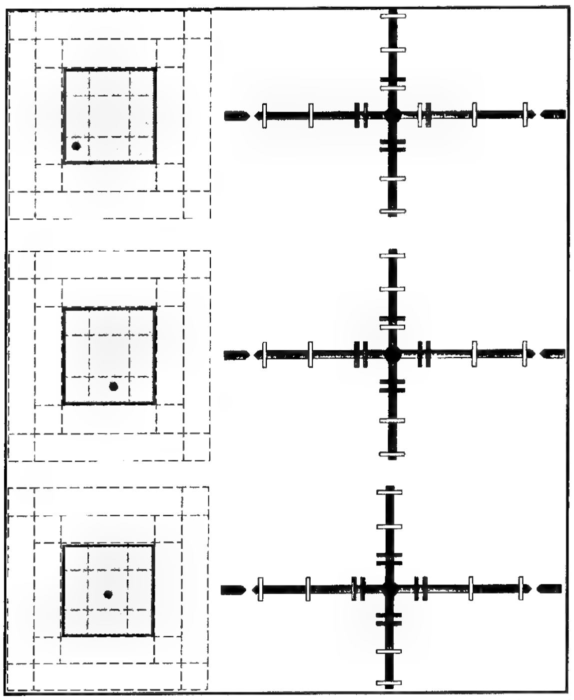


Figure 11 - Hover position display, showing examples of display conventions, the central area being the deck lock grid.

Figure 12 shows a comparison of the Cooper-Harper ratings for landings conducted with and without the assistance of the hover position indication system. The plot shows that pilot ratings for landings with or without the indication system were very similar. The landing scatters for the same landings are shown in figure 13. It is clear that there was a decrease in scatter for those landings where the pilot had use of the indication system. This improvement in performance was balanced by pilots seeing a marginal increase in workload.

Future work may include:

- Development of autopilot control laws for a differential GPS-driven automatic ship approach guidance system. Although already in flight test the simulator will be used to support development work

- Assessment of deck handling and recovery systems

- Further in the future it may be possible to use the simulator to provide advice to ship designers on such items as air wake and turbulence reduction methods and ship stabilisation systems

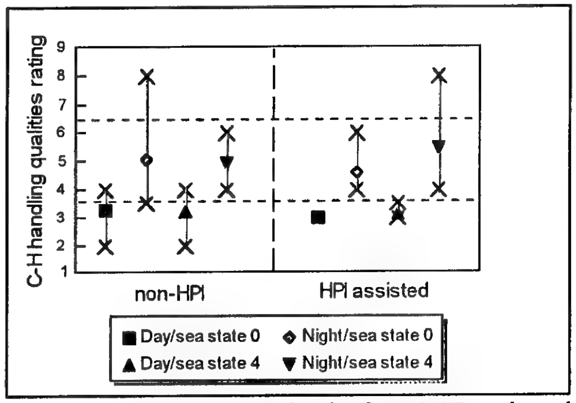


Figure 12 - Mean HQRs for landing MTE with and without hover position indication (HPI) system

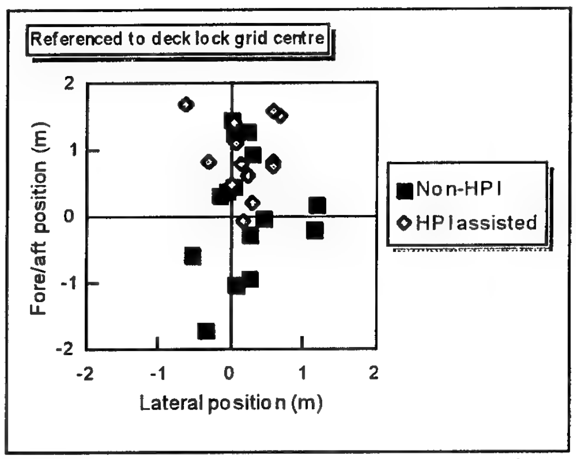


Figure 13 - Scatter for landings with and without hover position indication (HPI) system

Limitations

The AFS dynamic interface simulation does have limitations. The deficiencies have been covered in most part above. Of particular concern in the AFS were the field of view, as well as provision of an effective air wake and turbulence model. The non-dynamic sea surface provided by the visual system is a limitation when attempting to conduct studies at high sea states. The motion cueing will never be perfect, although it can be very good and the AFS probably provides one of the best motion systems in the world.

Having noted these deficiencies it should be remembered that real aircraft also have deficiencies. While we need to strive for improvements in the simulation, the trends for the results were considered to be realistic. Ship trials have shown that results are always better in the real world than in the simulator. Consequently, it may be safe to consider that the use of the simulator does not lead to over confidence - if a task can be accomplished in the simulator where it is more difficult because of the deficiencies, then it will be safe to perform the task in the real world. Indeed, from the helicopter/ship trials we have seen that for identical runs in the AFS and the real world, with broadly similar aircraft types and weather conditions the pilot rating points are typically about 0.5-1.0 greater in the simulator. This is far better than could be achieved a few years ago. Continual improvement in the fidelity of the dynamic interface simulation available on the AFS is sought. The improvements planned for the AFS visual system have already been outlined. A head-down glass cockpit is also being fitted this year.

Collaboration

The dynamic interface research programme has benefited from an international collaboration between the UK and the US, Canada and Australia. The collaboration is a vehicle for exchanging expertise, information and models, as well as promoting common data formats and sharing the results of relevant research. Work is also being undertaken into developing common pilot rating scales and dynamic interface test methodologies. There have also been regular exchanges o pilots and engineers for trials.

Conclusions

This paper has presented an overview of the current work being undertaken by the DRA to improve piloted simulation of the helicopter/ship dynamic interface. Work undertaken to determine the shortfalls of current simulators has also been reviewed, as has other current research work being carried out to improve helicopter/ship operating limits using piloted simulation. The following conclusions are indicated:

- Helicopter/ship dynamic interface simulation is demanding and capability adequate for worthwhile research and pilot training is only just becoming available
- It can be difficult to identify the influence of one element of the simulation on another and to determine the impact on overall fidelity of each element
- Effective helicopter/ship dynamic interface simulation could provide significant cost and operational benefits in pilot training, test and evaluation and research
- Adequate aircraft data is vital to the success of the simulation of the flying qualities of the aircraft
- An effective dynamic interface simulation capability has been built up on the DRA AFS, providing a valuable research and development tool for work in this area
- International collaboration continues to be a valuable element in progressing dynamic interface simulation capability.

The key challenges that remain may include:

- Ship air wake and turbulence is one of the major task drivers and a key shortfall in dynamic interface simulation. Much research work is being conducted to produce realistic models which will cue pilots to the correct control strategies
- Improvements in aircraft mathematical modelling will be necessary to take advantage of improvements in other areas of the simulation
- Improved motion cueing, possibly through the provision of multi-axis dynamic seats
- Validation is an important issue that demands significant further work

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Simulation of Rotor Blade Element Turbulence

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SUMMARY
A turbulence model has been developed for blade-element helicopter simulation. This model, called Simulation of Rotor Blade Element Turbulence (SORBET), uses an innovative temporal and geometrical distribution algorithm that preserves the statistical characteristics of the turbulence spectra over the rotor disc, while providing velocity components in real time to each of five blade-element stations along each of four blades.

An initial investigation of SORBET has been performed using a piloted, motion-based simulation of the Sikorsky UH60A Black Hawk. Although only the vertical component of stochastic turbulence was used in this investigation, vertical turbulence components induce vehicle responses in all translational and rotational degrees of freedom of the helicopter.

The single-degree-of-freedom configuration of SORBET was compared to a conventional full 6-degrees-of-freedom baseline configuration, where translational velocity inputs are superimposed at the vehicle center of gravity, and rotational velocity inputs are created from filters that approximate the immersion rate into the turbulent field. For high-speed flight the vehicle responses were satisfactory for both models. Test pilots could not distinguish differences between the baseline configuration and SORBET. In low-speed flight the baseline configuration received criticism for its high frequency content, whereas the SORBET model elicited favorable pilot opinion.

For this helicopter, which has fully articulated blades, results from SORBET show that vehicle responses to turbulent blade-station disturbances are severely attenuated. This is corroborated by in-flight observation of the rotor tip path plane as compared to vehicle responses.

THE SIMULATION
A piloted simulation was performed on NASA Ames Research Center's Vertical Motion Simulator (VMS) in 1994 using the GENHEL UH60A Black Hawk mathematical model of Reference 1 as a platform to investigate the SORBET model. This was a simulation technology experiment designed for the purpose of evaluating the influence of stochastic turbulence created at the blade-element stations of a rotor system.

This project was conducted primarily to determine if a representative workload could be accommodated by our computer system in real time, and to ascertain whether the cyclostationary (periodically stationary) effects of Reference 2 were significant in the motion environment of the VMS. Favorable pilot opinion was somewhat surprising because independent longitudinal and lateral inputs were not used during the piloted runs. Furthermore, angular components of turbulence were not explicitly included in SORBET, but rather occurred as induced responses from the superposition of vertical components at the blade stations.

The complete SORBET-Black Hawk model, including all the requisite motion and visual communication software, was executed on a single processor (VAX 9000) with a cycle time of 12 milliseconds. Cyclic phenomena are generally experienced in blade-element rotor models. The introduction of turbulence did not amplify these effects.

For the initial proof-of-concept simulation, only the vertical component of turbulence was used. Although pilots recognized the absence of the horizontal disturbances under certain flight conditions, their comments were generally quite favorable concerning the vehicle performance in turbulence. As opposed to the conventional body-fixed approach to turbulence modeling, SORBET has, at least incrementally, improved realism.

THE SORBET MODEL
For implementation into the GENHEL UH60A mathematical model of Reference 1, an heuristic model of turbulence (SORBET) was developed that preserves the Gaussian statistical characteristics of turbulence filters over the rotor disc. This model avoids the large computational and storage requirements of recent investigations into rotorcraft turbulence models (Refs. 2, 3), and imposes a modest computational overhead. SORBET was designed to create and propagate all three translational components of MIL SPEC turbulence (Ref. 4) in real time. The turbulence velocity components are superimposed at each blade-element location as a function of vehicle velocity, with distribution according to the element's instantaneous geometry.

Recent advances in the computational capacity of the simulation facility were significant in the decision to develop a model that distributes turbulence over the rotor disc. This was anticipated in Reference 5:

> Progressive gust penetration by the rotor is an important feature which should be included, where possible, as it is likely to strongly influence the simulation results. Consequently, the individual blade mode with the gust field model should be used when high computation time is permissible.

The entire stochastic rotor-element turbulence model is described here, although for the initial proof-of-concept simulation only the vertical component of turbulence was used. Examples from this model are presented for the helicopter in low-speed flight (10 knots).

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In this study the Dryden spectral form was selected due to its computational efficiency, although a discrete model of a curve-fit approximation to the von Karman form** does not offer any particular technical challenge. As will be discussed, the rotor-to-body attenuation is so severe that the original gust spectra appear to be of secondary consideration. From Reference 4, "When no comparable structural analysis is performed or when it is not feasible to use the von Karman form, use of the Dryden form will be permissible." The difference between the Dryden and von Karman form is basically a small variation in the high frequency content (Ref. 6).

SORBET Model Assumptions

Conventional MIL SPEC angular turbulence filters are a substitute for the finite-element distribution of translational turbulence in the air mass over the airframe. In the current study only the rotor disc is considered as an airframe, and the translational turbulence in the air mass is distributed over the rotor disc to each blade element. This distribution produces rotor moments as well as forces. Hence, only the MIL SPEC translational turbulence filters were used in the SORBET model.

From Taylor's hypothesis, the turbulent flow is stationary and homogeneous in the longitudinal direction. Turbulence filter outputs are statistically valid at either fixed spatial locations or at points translating with the vehicle (as is the case in the conventional body-fixed formulation). Two points of applicability are selected along an onset line that is perpendicular to the vehicle flightpath, and tangential to the leading edge of the rotor disc.

The outputs of turbulence filters are applicable at points on the onset line at the discrete time points. Interpolation perpendicular to the onset line requires a transport delay that is proportional to the distance along the flightpath to the element location, and inversely proportional to the vehicle's aerodynamic velocity.

Simulating transport delays requires that the turbulence filter outputs be tabled, and updated each computer cycle. A practical limit on the table size produces a corresponding minimum velocity of propagation through the rotor disc in simulation.

The MIL SPEC translational filters contain a pole proportional to the aerodynamic velocity. This velocity is limited to the value determined from the selected table size.

The turbulence is assumed uncorrelated at each side of the rotor disc, and homogeneous in the lateral dimension. The statistical properties of the turbulence are then invariant over the entire rotor disc by using what we call Gaussian interpolation between values applicable on each side of the rotor disc.

Geometrical Considerations

The Black Hawk rotor system has four blades ($N = 4$). For each of the blades the number of segments used in the simulation was five ($M = 5$). The blade and segment indices are defined

$$1 \le n \le N \quad \text{(blades)}$$

$$1 \le m \le M \quad \text{(segments)}$$

Using the equal-annuli algorithm of Reference 1, the radii to the blade stations may be computed from

$$r_m = \sqrt{(e+e')^2 + \frac{\left(m-\frac{1}{2}\right)}{M}\left[R^2 - (e+e')^2\right]} - e$$

where the rotor radius is $R = 26.83$ ft, the hinge offset is $e =$ 1.25 ft, and the spar length is $e' = 2.25$ ft.

The azimuth angle of the nth blade with respect to the vehicle's aft centerline is given by

$$\psi_n = \int \Omega dt + 2\pi\left(\frac{n-1}{N}\right)$$

where $\Omega = 27$ rad/sec is the nominal rotor RPM.

In the SORBET model, rather than defining the translational disturbance velocities at the vehicle center of gravity, they are defined at two onset points, located along an onset line that is perpendicular to the horizontal mean wind vector v_H shown in Figure 1. Using Gaussian inputs, three independent turbulence velocity histories are computed at each of these two points, in real time. These histories are updated each cycle time, and the pertinent values from these histories are distributed to the individual segment locations by temporal and geometrical algorithms.

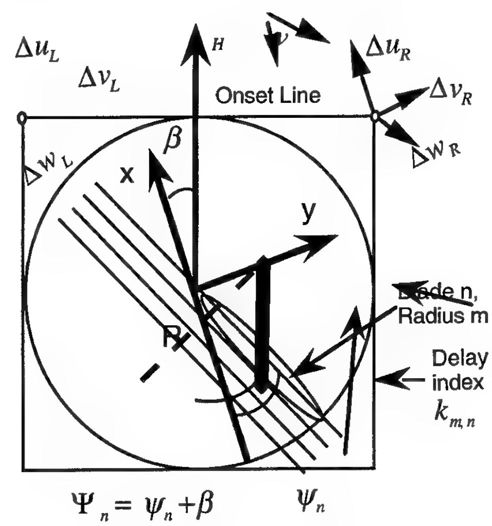

Figure 1. Rotor geometry.

Where u_b is the vehicle's longitudinal aerodynamic velocity and v_b is the lateral aerodynamic velocity, the in-plane aerodynamic velocity may be defined (approximately) by

$$v_H = \sqrt{u_b^2 + v_b^2}$$

**The earliest edition of such a model that we have discovered is in an unpublished Boeing document (YC-14-FC-111R) by James H. Vincent in December 1973.

Using this velocity and the sideslip angle β, the perpendicular onset line is as shown in Figure 1. The aerodynamic azimuth angle (wind axis) for the nth blade is then

$$\Psi_n = \psi_n + \beta$$

where ψ_n is the nth blade's geometrical azimuth angle from aft.

This geometry is shown below to be sufficient to establish both the longitudinal and lateral distributions.

Longitudinal Distribution

The left and right Dryden filters receive Gaussian inputs, so the outputs of these linear filters are also Gaussian. Furthermore, a transport delay in these outputs does not alter the statistical characteristics. The outputs of the filters are stored in tables, which are updated each cycle time. The value applicable for a given element is determined by selecting a value from the tables. Given that the table size is established ($K_M = 500$) for storing time histories of the outputs of the filters, the minimum aerodynamic velocity $v_{\min}$ that may be accommodated is determined by distributing the table over the rotor diameter.

$$v_{\min} = \frac{2R}{K_M \Delta t}$$

If a smaller minimum velocity is required, a larger table size must be selected. For the SORBET simulation cycle time Δt = 0.012 sec, the minimum velocity for $K_M = 500$ is 8.944 ft/sec (5.3 knots). The rotor-plane aerodynamic velocity used in the turbulence filters is restricted to this minimum.

$$v_{uv} = \begin{cases} v_{\min} & v_H < v_{\min} \\ v_H & v_H \geq v_{\min} \end{cases}$$

Independent of vehicle velocity, exactly $K_M \Delta t = 6$ sec of data are stored in the tables. Time histories of the outputs of six turbulence filters are contained in six separate tables, each of length K_M. At the minimum velocity the individual cells correspond to a length of 0.10732 ft (such that 500 of them span the rotor diameter), whereas at a velocity of 100 ft/sec (59.2 knots), for example, the cells are each 1.2 ft long such that only 45 of them are needed to span the rotor diameter.

In order to select the velocities to be used from the tables, for any blade element an integer index is computed to determine the element's perpendicular distance from the onset line. Defining

$$r_{m,n} = R + r_m \cos \Psi_n$$

the index is given by

$$k_{m,n} = \left\lceil \frac{r_{m,n}}{v_{uv} \Delta t} \right\rceil$$

where the upper brackets denote the integer ceiling operation. The tables extend beyond the rotor disc for higher vehicle velocities than the minimum, such that stationary outputs are available for table size increases caused by decreases in velocity. The hypothetical case where the entire rotor disc receives the same table value could only occur for velocities in the thousands of knots.

Lateral Distribution

Having determined the longitudinal point of application (or index $k_{m,n}$) for a given rotor element, the turbulence velocities from the tables are identified as applicable at both the left and right sides of the rotor disc. Lateral interpolation must be used to determine the element's final turbulence velocities. Although the lateral proportion (from the left-hand side) to an element may then be determined from the geometry of Figure 1

$$p_{m,n} = \frac{1}{2} + \frac{r_{m,n} \sin \Psi_n}{2R}$$

this proportion cannot be applied in a linear fashion. Using the vertical dimension, for example, although both $\Delta w_L(k_{m,n})$ and $\Delta w_R(k_{m,n})$ are Gaussian random variables with zero mean and RMS value given by σ_w, in order to preserve the statistical properties over the rotor disc we use Gaussian interpolation, so that the combination retains the same variance (and all other moments) as the original Gaussian variables.

A variable x is normally distributed with zero mean and variance σ^2 when its density function is

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(x/\sigma\right)^2}$$

The variance is defined by

$$E[x]^2 = \int_{-\infty}^{\infty} x^2 f(x) dx = \sigma^2$$

for a single random variable. When we combine two independent random variables at some interior point, we must consider their proportion p.

When a proportion p has the range ($0 \leq p \leq 1$), as it does in $p_{m,n}$ above, a linear combination of two normally distributed variables may be forced to have the same statistical properties as the originals by normalizing the density functions as follows:

$$f(x_1) = \frac{p}{\sqrt{p^2 + (1-p)^2}} f(x)$$

$$f(x_2) = \frac{1-p}{\sqrt{p^2 + (1-p)^2}} f(x)$$

As applied to variables with a zero mean value, this is a consequence of the arithmetic mean theorem given in Reference 7, where

$$E\left[\frac{px_1}{\sqrt{p^2+(1-p)^2}}+\frac{(1-p)x_2}{\sqrt{p^2+(1-p)^2}}\right]^2=$$

$$E\left[\frac{p^2x_1^2+(1-p)^2x_2^2+2p(1-p)x_1x_2}{p^2+(1-p)^2}\right]=$$

$$E\left[\frac{p^2x_1^2+(1-p)^2x_2^2}{p^2+(1-p)^2}\right]=\sigma^2$$

because $E[x_1x_2]=0$ for independent variables, and $E\left[x_1^2\right]=E\left[x_2^2\right]=\sigma^2$. The variance of the combined distribution then remains σ^2. Gaussian interpolation is therefore given by

$$\Delta w_{m,n}=\frac{p_{m,n}\Delta w_R\left(k_{m,n}\right)+\left(1-p_{m,n}\right)\Delta w_L\left(k_{m,n}\right)}{\sqrt{p_{m,n}^2+\left(1-p_{m,n}\right)^2}}$$

This combination is applicable for all three translational velocity components at an element location.

The Dryden Model

From Reference 4 the low-altitude vertical turbulence scale length is given as a piecewise continuous function of altitude h

$$L_w=\begin{cases}10 & h<10\text{ ft}\\ h & 10\le h\le 1000\text{ ft}\\ 1000 & h>1000\text{ ft}\end{cases}$$

and the in-plane components are given by the functions

$$L_u=L_v=\begin{cases}75.64 & h<10\text{ ft}\\ hf_{uv}^{-1.2} & 10\le h\le 1000\text{ ft}\\ 1000 & h>1000\text{ ft}\end{cases}$$

where

$$f_{uv}=0.177+0.000823h$$

The horizontal turbulence RMS intensities are a function of the selected vertical turbulence intensity σ_w

$$\sigma_u=\sigma_v=\sigma_w f_{uv}^{-0.4}$$

The results shown in this paper are for $\sigma_w=5$ ft/sec, $h=200$ ft, and $v_H=16.9$ ft/sec (10 knots).

Using Taylor's frozen field hypothesis from Reference 4, the Dryden form of the linear turbulence transfer functions are given by

$$\Delta u(s)=\frac{\sigma_u\sqrt{2v_{uv}/\pi L_u}}{s+v_{uv}/L_u}$$

$$\Delta v(s)=\frac{\sigma_v\sqrt{v_{uv}/\pi L_v}\left(\sqrt{3}s+v_{uv}/L_v\right)}{\left(s+v_{uv}/L_v\right)^2}$$

$$\Delta w(s)=\frac{\sigma_w\sqrt{v_{uv}/\pi L_w}\left(\sqrt{3}s+v_{uv}/L_w\right)}{\left(s+v_{uv}/L_w\right)^2}$$

For conventional aircraft (and our baseline configuration of the UH60A) the angular transfer functions are developed from partial differential equations relating these translational disturbances to the immersion rate of the vehicle into the turbulent field. These equations use a parameter b, which is the wingspan length of the aircraft.

$$\Delta p(s)=\frac{\sigma_w\left(\frac{\pi}{4b}\right)^{7/6}\sqrt{0.8v_{uv}}}{L_w^{1/3}\left(s+\frac{\pi v_{uv}}{4b}\right)}$$

$$\Delta q(s)=\frac{\frac{\pi}{4b}s\,\Delta w(s)}{s+\frac{\pi v_{uv}}{4b}}$$

$$\Delta r(s)=\frac{\frac{\pi}{3b}s\,\Delta v(s)}{s+\frac{\pi v_{uv}}{3b}}$$

These angular disturbances are not used in the SORBET model because the geometry is considered in the points of application of the translational turbulence excitations. The asymmetric turbulence velocities produce moments, which in turn produce angular activity.

All of the baseline case transfer functions have been presented because their spectra are displayed on certain graphs herein for reference purposes. Also, this baseline model is actually available as an option in our UH60A simulation model, and was used by pilots for comparison purposes.

Discrete Implementation

Continuous transfer functions involving random inputs are typically converted to discrete form using the zero-order hold formulation, where the input is assumed constant over each computer cycle Δt. The z-transforms of Laplace functions $f_i(s)$ then become

$$F_i(z)=Z\left\{\left(\frac{1-e^{-s\Delta t}}{s}\right)f_i(s)\right\}$$

which may then be converted to difference equations for discrete implementation. This process is nicely explained in Reference 8.

Using this technique on the Dryden transfer functions produces the coefficients

$$\gamma_u = v_{uv}\Delta t/L_u$$

$$f_1 = e^{-\gamma_u}$$

$$f_2 = \sigma_u(1-f_1)\sqrt{2/\gamma_u}$$

$$\gamma_v = v_{uv}\Delta t/L_v$$

$$g_1 = 2e^{-\gamma_v}$$

$$g_2 = -e^{-2\gamma_v}$$

$$g_3 = \left[\sigma_v/\sqrt{\gamma_v}\right]\left[1-e^{-\gamma_v}+\left(\sqrt{3}-1\right)e^{-\gamma_v}\gamma_v\right]$$

$$g_4 = -\left[\sigma_v e^{-\gamma_v}/\sqrt{\gamma_v}\right]\left[1-e^{-\gamma_v}+\left(\sqrt{3}-1\right)\gamma_v\right]$$

$$\gamma_w = v_{uv}\Delta t/L_w$$

$$h_1 = 2e^{-\gamma_w}$$

$$h_2 = -e^{-2\gamma_w}$$

$$h_3 = \left[\sigma_w/\sqrt{\gamma_w}\right]\left[1-e^{-\gamma_w}+\left(\sqrt{3}-1\right)e^{-\gamma_w}\gamma_w\right]$$

$$h_4 = -\left[\sigma_w e^{-\gamma_w}/\sqrt{\gamma_w}\right]\left[1-e^{-\gamma_w}+\left(\sqrt{3}-1\right)\gamma_w\right]$$

These coefficients are used in the following six difference equations, each driven by an independent Gaussian noise source η_i, with a zero mean value and a unity standard deviation.

$$\Delta u_L(k) = f_1\Delta u_L(k-1) + f_2\eta_1(k)$$

$$\Delta u_R(k) = f_1\Delta u_R(k-1) + f_2\eta_2(k)$$

$$\Delta v_L(k) = g_1\Delta v_L(k-1) + g_2\Delta v_L(k-2) + g_3\eta_3(k) + g_4\eta_3(k-1)$$

$$\Delta v_R(k) = g_1\Delta v_R(k-1) + g_2\Delta v_R(k-2) + g_3\eta_4(k) + g_4\eta_4(k-1)$$

$$\Delta w_L(k) = h_1\Delta w_L(k-1) + h_2\Delta w_L(k-2) + h_3\eta_5(k) + h_4\eta_5(k-1)$$

$$\Delta w_R(k) = h_1\Delta w_R(k-1) + h_2\Delta w_R(k-2) + h_3\eta_6(k) + h_4\eta_6(k-1)$$

These computationally efficient equations produce stable outputs for all stable inputs.

For the body-fixed formulation these velocities are superimposed at the center of gravity. In SORBET these velocities are created at the two onset points and then distributed and superimposed at the various blade-element locations. They produce forces and moments because they modify the angle of attack of each element.

Element Velocities

Forces developed at individual blade-element locations are invariably summed to create total rotor forces and moments. In this section the spectral filtering consequences of the summation operation are illustrated by using the turbulence velocities themselves. Then, in the next few sections, this is further illustrated using the blade flapping spectra and the total vehicle responses. Although a blade variable may exhibit much harmonic content, the summation over the blade index effectively removes many of the harmonics (Ref. 9).

Figure 2 displays typical time histories of vertical turbulence produced at the two onset points ($\Delta w_L \Delta w_R$). These histories are the uncorrelated outputs of the Dryden vertical filters, excited by Gaussian noise with σ_w = 5 ft/sec.

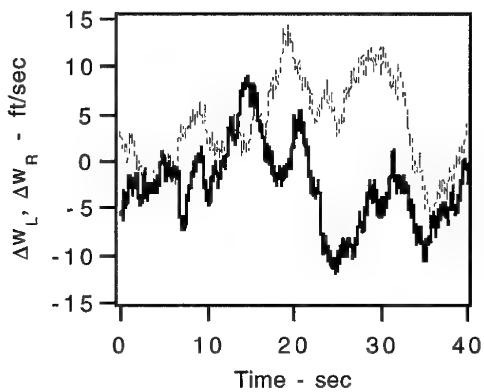

Figure 2. Onset point velocities.

The velocities of Figure 2 are the origins of the turbulence velocities for each blade element. In response to these inputs, Figure 3 is an example of the velocity of just one element (outboard, m = 5) of one blade.

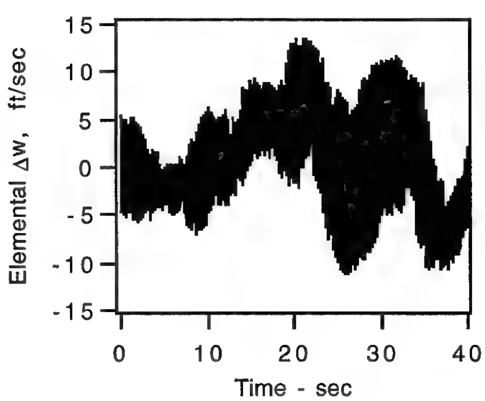

Figure 3. Element velocity.

Because the velocities at an element are rotationally sampled, Figure 3 displays considerable one-per-rev frequency content, bounded approximately by the input curves shown in Figure 2.

Each and every element experiences vertical velocities similar to that shown in Figure 3. However, the summation of all of the 20 elements for each time point selectively eliminates most of the high frequency content. Figure 4 displays this phenomenon. What remains after summation is essentially the average of the original onset velocities.

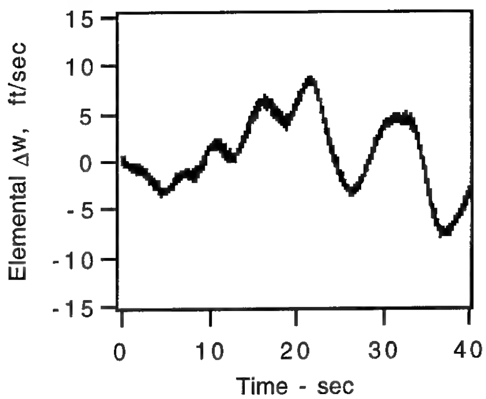

Figure 4. Summed velocities.

This phenomenon occurs independent of turbulence. In the next three sections this is further illustrated using both rotor and vehicle variables.

Rotating Frame Blade Spectra

The flight condition documented here is for a trimmed vehicle in 10-knot horizontal flight at an altitude of 200 ft. Under these conditions, when turbulence is not present, any given blade produces the flapping (β_n of Ref. 1) time history as shown in Figure 5.

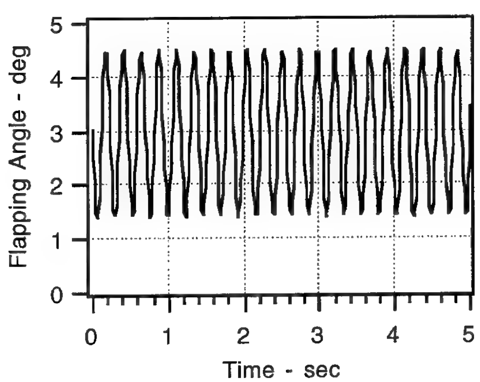

Figure 5. Flapping without turbulence.

The power spectral density (PSD) or autospectrum of this signal is shown in Figure 6.

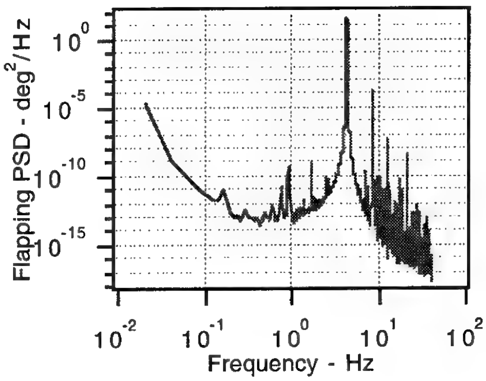

Figure 6. Flapping PSD without turbulence.

The significant frequencies at the blade level of examination are the blade harmonics, beginning with the fundamental, at 4.297 Hz (27 rad/sec). These harmonics theoretically extend to infinity. Frequencies on this graph that are observed below the fundamental are, for the most part, aliased harmonics (originating beyond the Nyquist frequency).

When the vertical turbulence (σ_w = 5 ft/sec) is introduced into the rotor system under the same conditions, the time history of a blade displays more frequency content, as indicated in Figure 7.

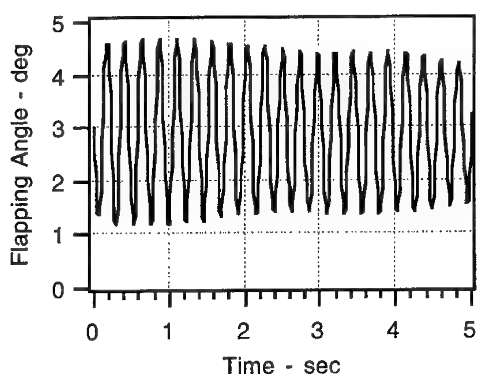

Figure 7. Flapping with turbulence.

The background spectrum of Figure 6 is then elevated by a few orders of magnitude, as shown in Figure 8.

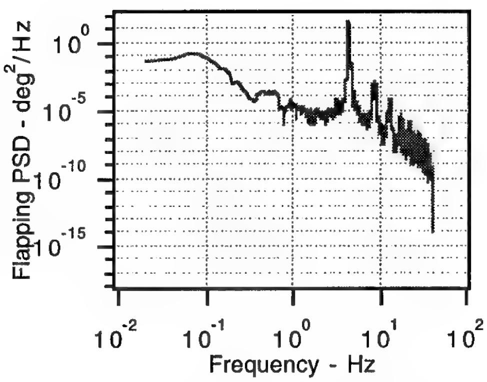

Figure 8. Flapping PSD with turbulence.

The significant periodic components in these spectra are created by the blades essentially tracking each other, independent of turbulence. Turbulence elevates the background spectrum, but since the inputs are not uniform over the rotor disc it does not have a significant influence on the rotor harmonics. Notice that in Figure 8, except for the first harmonic, the blade harmonics almost disappear into the turbulent background, and they are not amplified by the introduction of turbulence. This leads to the conclusion that at the blade level of consideration the introduction of turbulence does not produce significant cyclo-stationary phenomena.

The lagging spectrum is not shown here. At this flight condition it is about an order of magnitude smaller than the flapping spectrum.

Fourier Coefficients

Forces and moments generated by blade activity are transmitted to the airframe through summation functions. Given that each simulated blade has identical physical properties, such as mass, length, and relationship to adjacent blades, the consequence of summation is to eliminate all integer harmonic multiples of the RPM that are not a multiple of the number of blades (Ref. 9). This is illustrated by considering the principal flapping Fourier coefficients.

The principal flapping Fourier coefficients (main distortions of the rotor plane, in nonrotating frame) are given by the following summations of the individual flapping angles (β_n of Ref. 1).

$$A_{0F} = \frac{1}{N}\sum_{n=1}^{N} \beta_n$$

$$A_{1F} = -\frac{2}{N}\sum_{n=1}^{N} \beta_n \cos\psi_n$$

$$B_{1F} = -\frac{2}{N}\sum_{n=1}^{N} \beta_n \sin\psi_n$$

where A_{0F} is the coning (steady flapping) angle, A_{1F} is the longitudinal first harmonic, and B_{1F} is the lateral first harmonic.

The PSDs of these Fourier coefficients are given in Figures 9–11. The lower lines show the behavior without turbulence, and the upper lines show the behavior with vertical rotor turbulence. In comparing these figures with Figures 6 and 8 it is seen that only blade harmonics that are a multiple of the number of blades survive the summation operation, whereas the stochastic contributions are retained in the spectra of the rotor disc.

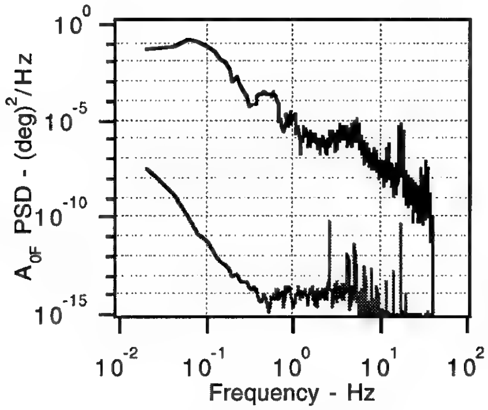

Figure 9. A_{0F} spectra.

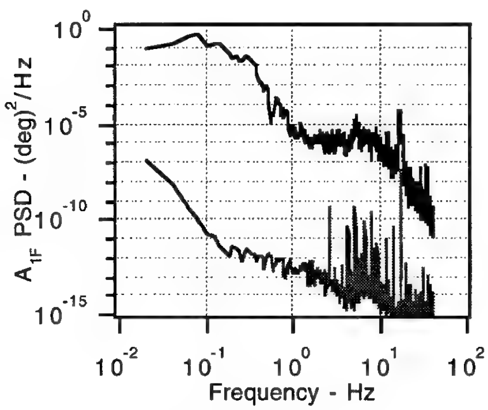

Figure 10. A_{1F} spectra.

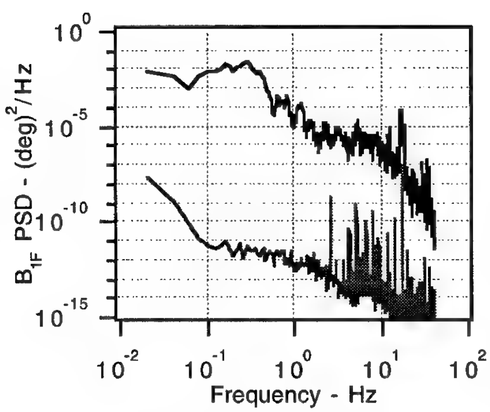

Figure 11. B_{1F} spectra.

Harmonics of N/rev seen in these figures are not caused by turbulence (see Ref. 9). They are a normal consequence of blade summation of periodic phenomena. Of course, interior harmonics will be observed if the blades are not tracking each other in their rotational environment. This occurs during transients, and is also a consequence of mismatched blades:

> The one-per-revolution (27 rad/sec) frequency content that can be seen in the flight-test data is caused by a mismatched rotor blade that was not tracking with the other three on the test aircraft; therefore, this frequency is not observed in the simulation results. (Ref. 10)

Baseline Traces

The baseline spectra are the responses for the conventional implementation of turbulence, typically used for fixed-wing aircraft but also available in our UH60A model. In the baseline configuration the inputs are at the vehicle center of gravity. The transfer functions for this formulation were presented in the section named The Dryden Model. The baseline spectra also describe the outputs of SORBET's right and left filters.

The baseline configuration has been available for the UH60A model (and other helicopters) for a number of years, although pilots have invariably been critical of its performance during low-speed flight. This baseline configuration is nonetheless interesting for comparison purposes. In Figure 12 the vertical velocity baseline spectra are shown, with parameter $a = v/L_w$.

For the flight condition of 10 knots at an altitude of 200 ft, the parameter is about 0.04.

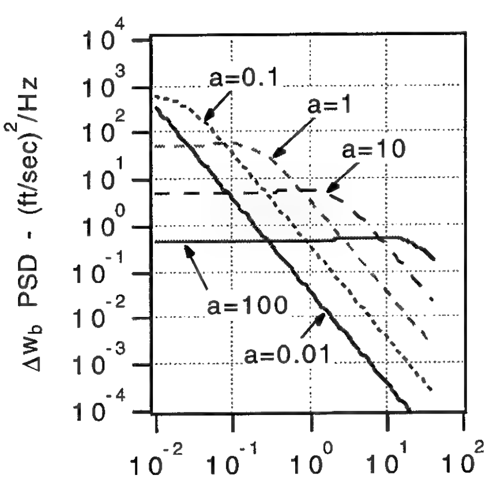

Figure 12. Baseline spectra.

At the 10-knot flight condition the baseline PSDs are presented in Figures 13–18 as dotted lines. In the configuration studied here only the vertical axis of SORBET had an input. However, all axes (solid lines) display outputs.

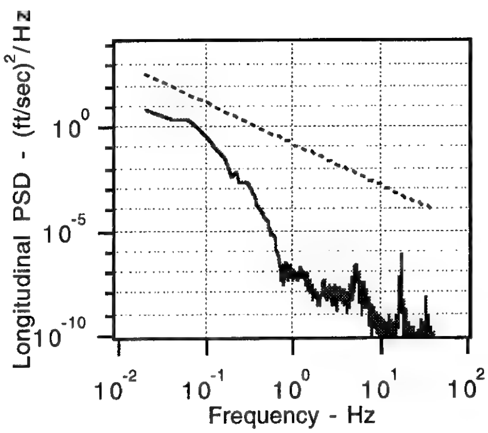

Figure 13. Δu_b, vertical input.

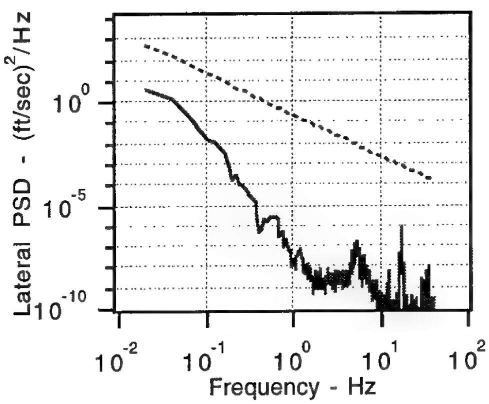

Figure 14. Δv_b, vertical input.

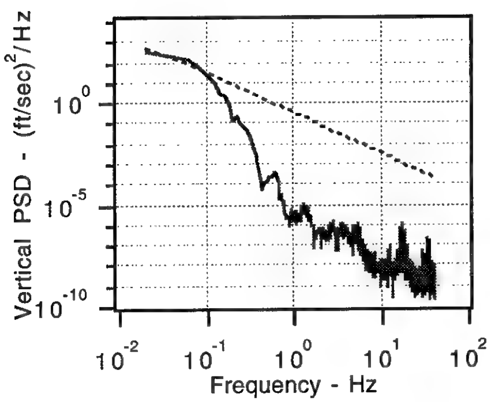

Figure 15. Δw_b, vertical input.

It is useful to think of the body-fixed spectra (dotted lines) as representative of the *velocity of the air mass, as experienced by a point traversing through it.* If this air mass velocity is rigidly attached to the vehicle, as it is in the conventional formulation,

then the vehicle itself experiences this velocity. If, however, it is attached to the velocity of a blade element, then it produces an alteration in that element's angle of attack, which in turn contributes to the production of rotor-system forces and moments.

The body-fixed baseline spectra could only be the same as the helicopter spectra if unity transfer functions existed from the rotor to the body. Indeed, the existence of nonunity transfer functions in this regard is obvious because rotorcraft responses differ from those of conventional aircraft. Nonetheless, these spectra are useful in determining just what the rotor-to-body effects are. Only "for high speed flight, where helicopters behave more like conventional aircraft"† could these dotted baseline curves possibly represent desirable responses.

For completeness the angular PSDs are also shown in Figures 16–18. All angular disturbances observed in SORBET were induced responses from the application of vertical turbulence. The baseline curves on these plots were obtained from the conventional transfer functions, using an arbitrary value of wingspan length b of 20 ft.

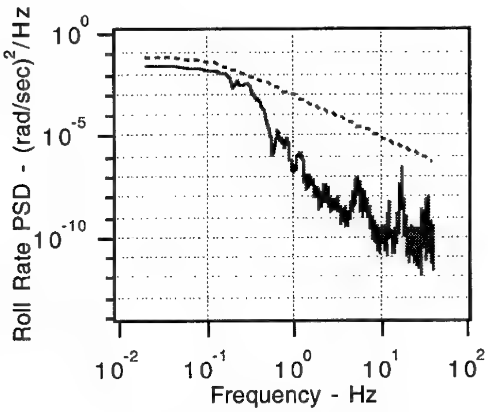

Figure 16. Δp_b, vertical input.

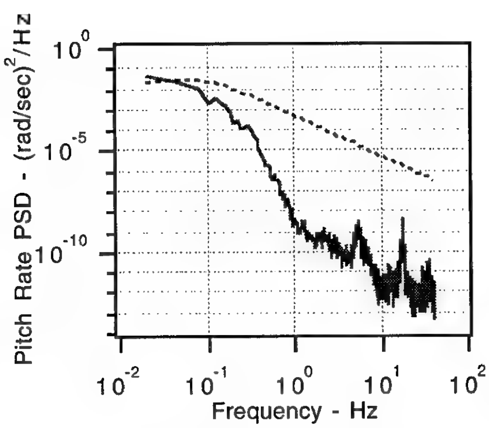

Figure 17. Δq_b, vertical input.

†Remark by Norman D. Ham of Massachusetts Institute of Technology during his class on Aerodynamics, Stability, and Control of Rotorcraft and Other VTOL Aircraft, Ames Research Center, 1978.

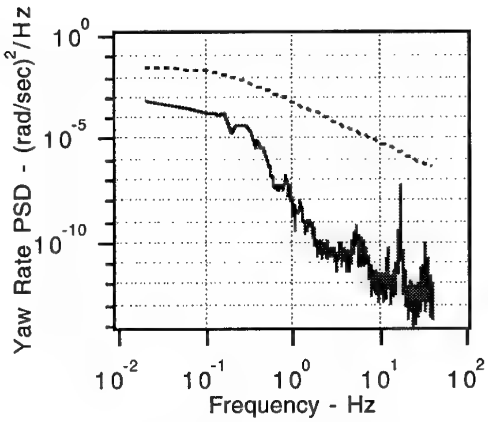

Figure 18. Δr_b, vertical input.

In Figures 13–18 only the vertical component of turbulence into the rotor system was used, as was the case during pilot evaluations. Induced effects are seen to occur on all other axes. Pilots generally concurred that this system felt quite realistic, with the exception that some airspeed and lateral variations were lacking. This is illustrated in Figures 13 and 14.

Rotor-Airframe Transfer Function

In Figure 15 the vertical vehicle response to vertical rotor turbulence was shown. Since the dotted line represents the spectral input throughout the rotor disc, clearly much energy is lost in the rotor-to-body transfer function. This transfer function was determined by emulating a single-input/single-output (SISO) system using the same statistical value for each element at each time point.

The baseline vertical Dryden PSD as shown in Figure 15 is plotted in Figure 19 as a dashed line. Using identical random inputs at each element, the SISO PSD curve of Figure 19 was created. Comparing the SISO curve to the input spectrum of the air mass (dashed line), there is considerable attenuation. Also shown in Figure 19 is the multiple-input/single-output (MISO) PSD curve, as replicated from Figure 15. More attenuation occurs on this curve, when the inputs are not uniform (MISO) throughout the rotor disc.

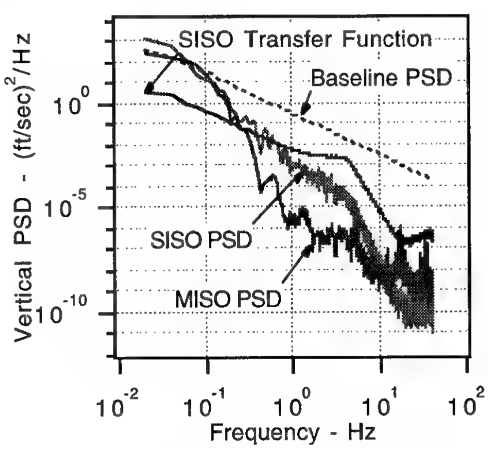

Figure 19. Δw_b, same vertical inputs.

The rotor-to-body transfer function (nondimensional) is also shown in Figure 19, as computed from the SISO curve with respect to the baseline curve. The attenuation becomes more pronounced beyond about 4.3 Hz, which happens to be the rotor RPM. This phenomenon is a consequence of the blade summation process operating on signals that are identical for each element.

When turbulence was permitted to vary over the rotor disc according to the algorithms, the slightly different results of Figure 15 were produced, shown in Figure 19 as the MISO curve. The transfer function for the MISO system has not been identified, although it must be similar to the SISO system given in Figure 19 because of the vehicle response similarities shown by the SISO and MISO curves.

PILOT OPINION

From Figure 19, the rotor system clearly attenuates high-frequency nonuniform inflow (as in blade-element turbulence) to a greater extent than it attenuates uniform inflow. Nonetheless, lower frequency distortion of the rotor disc caused by turbulence may be an important piloting cue. Distortions are an indication of activity in the stability augmentation system (SAS), and may influence speed selection. Some of the simulation pilots stated that in real helicopter flight they sometimes "observed the rotor plane undergoing large responses to turbulence, while the airframe's motion was relatively smooth." In response to pilot requests for this visual cue, the tip-path plane will be included in the visual display for the next rotorcraft simulation on the VMS.

To assure that simulation pilots had similar conditions in which to assess the model, they were given identical tasks of following recorded flightpaths. Our chief test pilot for the simulation established these basic paths (without turbulence) by flying a set of runs over the terrain, and the spatial positions and orientations of the helicopter were recorded. Using a sophisticated playback feature of our heads-up display, other pilots were shown these paths by using both a graphical lead aircraft and a visually superimposed stick-figure canyon (Ref. 11). This is depicted in Figure 20, where both the lead aircraft and the velocity vector (circle) are indicated.

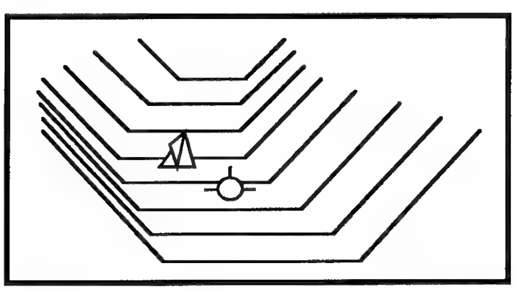

Figure 20. Playback canyon.

Pilots had the task of following the lead aircraft (at speed) and staying within the canyon. Without turbulence, this task was quite simple for all pilots. The task became more difficult when turbulence was added.

All pilots found the SORBET model realistic, and their comments were used to improve the model during the simulation.

Pilots generally agreed that the turbulence magnitude should be a function of velocity. Above 40 knots, the subjective values for light and moderate turbulence were selected as $\sigma_w = 5$ ft/sec and 8 ft/sec, respectively. Near hover, pilots selected standard deviations that were half these values. The reason for this is unknown, and should be investigated further. Although the frequency content is acceptable, the magnitude must be decreased in low-speed flight. For the body-fixed formulation in low-speed flight, pilots invariably criticized the baseline configuration. A typical comment was "It was like a washboard."

Pilots are clearly sensitive to the more nonlinear aspects of atmospheric turbulence. From Reference 12, "turbulent flows are diffusive and intermittent" and, moreover, "the element of surprise that is characteristic of turbulence must be present." Pilots were quick to point out that although the stochastic turbulence was realistic, it was too continuous and lacked occasional sharp gusts. Their comments reflected Reference 13 quite closely:

> One of the most common grievances helicopter pilots have with simulated atmospheric turbulence is that it is too regular, and does not contain 'patches' of turbulence followed by periods of calm air.

Due to the large number of pilot remarks in this area, we accommodated them on certain points. During the simulation, a few additions to the SORBET model were made, as described below. The pilots agreed that these additions provided even more realism.

Occasional vertical gusts were simulated by changing the magnitude of the mean vertical wind at random times. Gusts were programmed to arrive more frequently and more abruptly at high speeds (about every 3 sec) than at low speeds (every 12 sec). The resulting random vertical gusts were praised by the pilots as extremely characteristic of real turbulence.

Moments of calm air were introduced by scaling the magnitude of the stochastic turbulence to zero for random time periods (between 2 and 6 sec). This was followed by smoothly applying random percentages of the full magnitude, also for random time periods. This technique created the effect of patches of different levels of turbulence.

With the addition of vertical gusts and patches of turbulence, the vertical turbulence was accepted by all the pilots as very realistic. One deficiency they found was in the reduced level of lateral, longitudinal, and yaw turbulence cues. Since the model did not directly influence these axes, these comments were expected. As a partial solution, a stochastic input, perpendicular to the tail rotor, was added. While the pilots noticed the extra yaw variations, they generally agreed it was not a great improvement, and the lack of lateral inputs detracted from realism.

One major pilot concern involved the way the turbulence was not correlated to the terrain. This was not within the scope of SORBET, but work is being done in this area (Ref. 14).

In summary, pilot comments were quite favorable for SORBET during the 2-week motion-based simulation study. Representative comments are listed below, where the italics are the authors'.

1. The chief NASA test pilot for this simulation, Munro Dearing, commented during low-speed flight that "this would be typical of light-to-moderate gusts in hover." However, at 100 knots he noticed "there is a lack of heave." These comments were made prior to the introduction of the embellishments described above.

2. NASA test pilot Bill Hindson commented on SORBET once the occasional gusts were included that "the low frequency pitch and roll *felt* is also characteristic *of turbulence,*" and "it is a fairly realistic simulation."

3. NASA test pilot Tom Reynolds commented on SORBET when the occasional quiet periods were introduced that "*this is* much like what I expect is real," and "overall, this feels pretty good, fairly realistic light-to-moderate *turbulence*."

4. NASA test pilot Gordon Hardy commented on the SORBET simulation that "*these are* pretty typical excursions compared to real flight," but also said "I'd expect more lateral motion."

5. Retired NASA test pilot Ron Gerdes commented "*there is* nothing that I would change *in the model*."

6. Navy pilot Tim Sestak commented "this is what turbulence feels like."

IN-PLANE TURBULENCE

Although piloted runs were not made with the in-plane longitudinal and lateral turbulence options enabled, it has been established that their inclusion would have added very little to the simulation. From Reference 15, "Current articulated and semi-rigid rotors are insensitive to in-plane gusts." Our own data support this statement.

In fact, adding these in-plane components to SORBET produced changes that were too trivial to show here. For this reason we postulate that in-plane translational turbulence components should probably act at the vehicle center of gravity, just as in the conventional formulation. Of course, using these in-plane components also means that consideration should be given to correlated tail rotor responses. The tail rotor becomes much more significant when gusts are considered, rather than just stationary turbulence alone.

In our next investigation we plan to include in-plane components for turbulence that will probably be applied at the vehicle center of gravity. This proposed system has also been investigated; it produces almost identical spectral responses as those shown in Figures 13–18, except that the in-plane vehicle responses of Figures 13 and 14 then become superimposed with the dashed lines (as in the conventional aircraft case). This model should then include the in-plane disturbances that pilots expect.

CONCLUSIONS

Adding turbulence to the Black Hawk simulation added less than 10 percent to the required cycle time. Hence, blade-element implementations of turbulence are now feasible using modern computers.

In-plane turbulence applied at the rotor elements produces minimal vehicle responses. This is therefore an unsatisfactory technique for modeling stochastic turbulence in the horizontal plane, and would probably produce erroneous results using gust models. Hence, in-plane disturbances should probably be handled more or less as in the conventional formulation, with the inclusion of the correlated influence on the tail rotor.

The vertical component of turbulence as input at the blade radial stations produces significant differences in vehicle performance from that of conventional body-fixed techniques. The differences include considerable attenuation of higher frequencies in the vertical and all rotational axes. These phenomena elicit favorable pilot opinion, and probably identify the major difference between helicopter and conventional aircraft responses.

In establishing a uniform level of turbulence over a flight regime our test pilots preferred a standard deviation that varied linearly with velocity, roughly doubling from hover to 40 knots, where it became constant. This is an unknown phenomenon that deserves further investigation. Also, criteria for implementing patches of different levels of turbulence should be established, because they correspond to pilot experience.

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C-160 GROUND HANDLING MODEL UPDATE USING TAXI TEST DATA

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SUMMARY

The need for representative ground handling modelling for flight simulators according to modern approval standards is generally strong. A main problem is to find an adequate level of model accuracy for the complex physics of ground related maneuvers. In this paper some examples of the development process of a C-160 ground handling model are presented. The original analytically derived model is updated and validated with taxi test data using system identification methods. Not only the identification of model parameters is discussed, but it is also demonstrated how to derive equivalent submodels in order to reduce the complexity of the data bases without hardly any loss of simulation fidelity.

NOMENCLATURE

a_x	body-fixed x-acceleration
η	nosewheel steering angle
F_s	oleo damper spring force
F_d	total oleo damper force
F_b	brake pressure scale factor
$F_{x,acc}$	equivalent tire acceleration force
F_x	tire longitudinal force
F_y	tire side force
F_z	tire normal force
f_{oleo}	oleo compression
I	impulse
K_1, K_2	damping coefficients
m	aircraft mass
μ	friction coefficient
μ_r	roll friction coefficient
$\mu_{b_{max}}$	maximum brake friction coefficient
p_b	brake pressure
r	aircraft's yaw rate
τ	skid angle
t	time
u_K, v_K	body-fixed components of flight path velocity
$\underline{X}$	state vector
x_{nw}, x_{mw}, y_{mw}	body-fixed x-, y-distances of a tire contact point from CG

Abbreviations:

A/C	aircraft
CG	center of gravity
FAA	Federal Aviation Administration
U/C	undercarriage
6-DOF	six degree-of-freedom

1. INTRODUCTION

Under contract, DLR Institute of Flight Mechanics participated in the development of a new flight simulator for the military transport aircraft C-160. This simulator is being built by the Simulator Division of Thomson-CSF according to the FAA simulator approval standard Level D [1]. DLR's main tasks were to instrument a test aircraft, to conduct flight tests, to prepare validation and proof-of-match data, and, last not least, to develop a suitable math model for the aircraft dynamics. An extensive flight and ground test program was carried out in order to derive a mathematical model from flight test data. Using system identification methods, a completely new aerodynamic derivative model was estimated [2]. This is nowadays a common technique for determining a high quality simulator data base [3-5].

Besides the aerodynamic model, simulator model fidelity essentially depends on a second math model part, namely the ground handling model with undercarriage kinematics and tire characteristics. This model is always necessary for operations with ground contact: takeoff, landing, and taxiing, which are extremely important maneuvers for pilot training. Nowadays, the quality of ground handling models is considered as not sufficient, as the validation of simulator models for ground contact within the stringent FAA simulator qualification tolerances always causes problems [6-7]. The need for more representative, but computer implementable undercarriage (U/C) models is strong [8].

A first problem of ground handling modelling is the

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decision on how detailed the model structure has to be. The aircrew is only aware of the loads induced by the undercarriage, not e.g. of the oilflow within one shock absorber. This crew awareness should be the main criterion within the model development process [9]. Fidelity problems are mainly based on the availability of data bases: (a) spring and damper characteristics of suspension and tires and (b) characteristics of the tire-runway contact (tire models). Generally, tire models are based on measurements, but these are rarely available for aircraft tires [10]. Often data bases and models are taken from the automobile industry, cf. [11], which can be adapted to aircraft characteristics [12].

This paper presents some results of an investigation aimed at improving the simulation quality of a C-160 ground handling model. Using the measured taxi test data of maneuvers gathered for simulator qualification, it is tried to update essential parts of the purely analytically derived model with system identification methods in order to meet aircraft specific characteristics. Generally, it is sufficient for a model update to adjust important parameters within its structure, however, sometimes the model structure has to be changed or expanded, too. In this paper, some examples for the improvement of different parts of the C-160 ground handling model will be presented and discussed.

2. BASIC GROUND HANDLING PHYSICS

The ground handling model is one of the three main submodels in the structure of a complete simulator model (aerodynamics, ground handling, engine). A simplified structure of a ground handling model with inputs, outputs, and information used within the black box 'ground handling model' can be illustrated as in Fig. 1. The inputs for a conventional transport aircraft are the nosewheel steering angle and the right and left brake pressures. The outputs are the U/C forces and moments acting at and about the aircraft's center of gravity.

A lot of information has to be provided for that black box: (a) the aircraft state vector $\underline{X}$ (rotational and translational speeds, Euler angles, and CG altitude) and (b) the U/C data base (suspension geometry and location relative to CG, runway condition, tire characteristics, friction coefficients, stiffness and damping characteristics of the suspension devices). The black box contains the differential equations of the dynamic systems (e.g. tires), the kinematics of each suspension device, and the application rules for the data base.

Fig. 2 illustrates the U/C design of the C-160. It consists of a two-wheeled, steerable nose gear and four two-wheeled main gears. The main gear struts are mounted with a considerable inclination angle to the fuselage reference line, and the oleo dampers are compressed by a rotational motion of the lower struts.

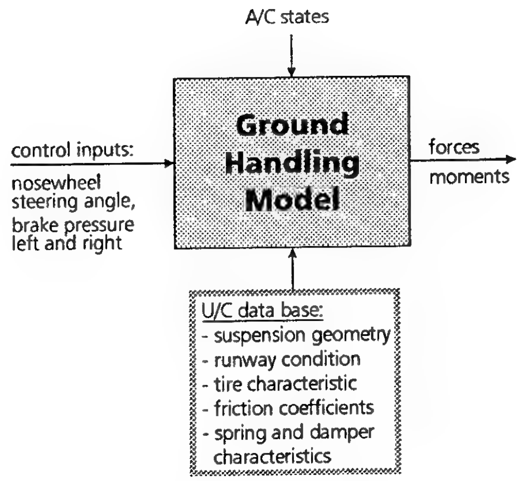

Fig. 1. Ground handling model black box structure

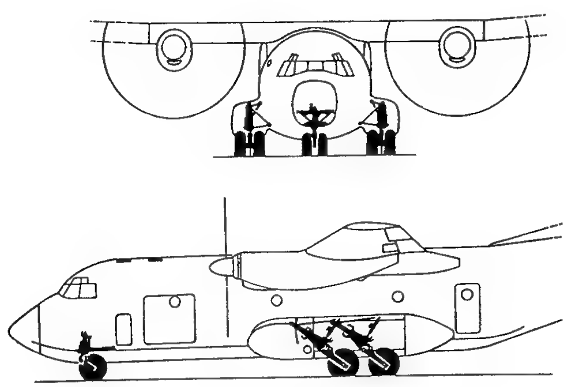

Fig. 2. C-160 aircraft and undercarriage design

The ground handling model of the C-160 was formulated analytically and describes the dynamics of the suspensions for the nose gear and the four main gears separately. The model includes two suspension devices for each single landing gear causing dynamics between the airframe and the runway (Fig. 3).

The oleo-pneumatic damper is mounted with an inclination angle of about 40° to the fuselage reference line. The kinematic model between the tire axes and the airframe uses the geometric lengths, angles of inclination, and damper strokes of the struts. The oleo-pneumatic damper force F_d is the sum of damper stiffness and damping force. The damper

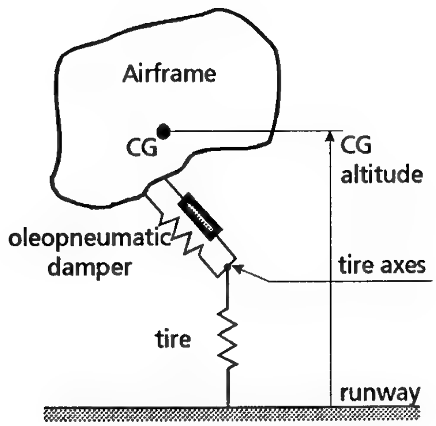

Fig. 3. Model structure of one C-160 landing gear

stiffness F_s of the struts is a nonlinear function of the damper compression and is known from manufacturer's data. The damping is modeled velocity squared ($\dot{f}_{oleo}^2$) with different constants for compression (K_1) and decompression (K_2):

$$F_d = \begin{cases} F_s + K_1 \dot{f}_{oleo}^2 & : \; compression \\ F_s - K_2 \dot{f}_{oleo}^2 & : \; decompression \end{cases} \tag{1}$$

The tire is the second suspension device. Two tires are mounted on each strut. The nonlinear tire stiffness is modeled using manufacturer's data tables. A tire damping force is neglected as well as the tire mass. The geodetic z-motion of the tire axis for each strut is thus described as a first order differential equation.

3. ROLLING AND BRAKING

Both, the tire side force, responsible for the lateral directional behavior of the aircraft, and the longitudinal tire force are dependent on the tire normal force at each contact point to the runway. This normal force is mainly a function of the oleo-pneumatic damper force, which can be computed as a function of A/C attitude, velocity, altitude, rotation, and U/C kinematics and characteristics.

Having determined this normal force F_z for each tire contact point, the longitudinal force F_x can be computed by multiplying by the friction coefficient μ.

$$F_x = F_z \cdot \mu \tag{2}$$

The friction coefficient μ is the sum of the roll friction coefficient μ_r and the brake friction coefficient, that depends on the magnitude of brake operation by the pilot.

$$\mu = \mu_r + F_b \cdot p_b \cdot \mu_{b_{max}} \tag{3}$$

$\mu_{b_{max}}$ is the maximal brake friction coefficient just before the tire begins to slip on the runway. This value depends heavily on the surface consistency (dry, wet, icy ...). The factor F_b scales the brake pressure p_b, which is set by the pilot, to values between 0 and 1.

A suitable implementation of the roll friction coefficient is necessary for simulation of maneuvers with ground contact. This roll friction coefficient is set according to the runway surface consistency. The C-160 rolling on dry concrete is modelled with $\mu_r = 0.03$, whereas for rolling on soft soil $\mu_r = 0.11$. During model validation, the roll friction coefficient can be adapted to simulate correct ground speed or ground distance, but it should deviate not more than 10 % from the handbook values.

For modelling a correct braking force, the brake pressure scale factor F_b can be adapted using suitable taxi test data. A collection of test data at different ground speeds, combined with some differential left and right braking can be evaluated with system identification methods using the full 6-DOF model for the aircraft including engine model and U/C model. Important sensor signals for the parameter determination are longitudinal acceleration, ground speed, and ground distance. With these test data it is possible to estimate the brake scale factors F_{b_l} and F_{b_r} for left and right brake separately. In theory, both should have the same value, but it has been found that they often differ up to 5-6%. The consideration of the difference between left and right is important for lateral stability during taxi maneuvers with braking.

Fig. 4 shows a typical identification result for (a) differential brake operations and (b) rolling with a total stop at the end. Longitudinal acceleration and ground speed show a proper fit and each brake operation can be seen clearly in both the measured and the simulated data. Additionally, the aircraft pitch angle and the nose wheel oleo compression is plotted. Each brake operation results in a small pitch down rotation, which is verified by a corresponding nose wheel oleo compression (cf. Fig. 4). Even the pitch up after the total stop at the end of the second time segment can be seen in both the measured and the simulated data.

To verify correct rolling and braking, Fig. 5 shows two FAA validation tests: (a) ground acceleration and (b) deceleration time and distance using only the wheel brakes (no reverse thrust). For (b) the identified brake pressure scale factors are used. The roll friction coefficient is set for rolling on dry concrete (0.03). Both validation tests show a proper fit, satisfying the Level D requirements. In (b), the anti-skid system activation for the right brake can be seen clearly.

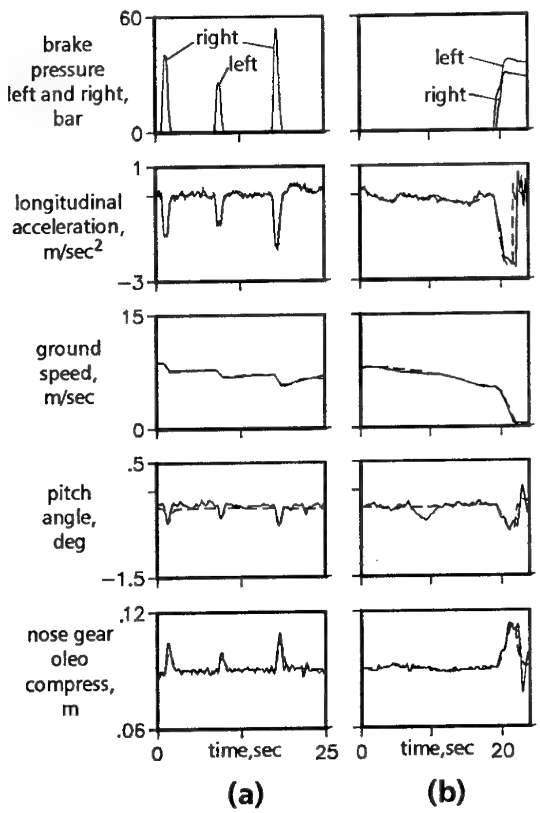

Fig. 4. Identification of brake pressure scale factors with differential braking, simulation model output (- - -) compared to taxi test data (——)

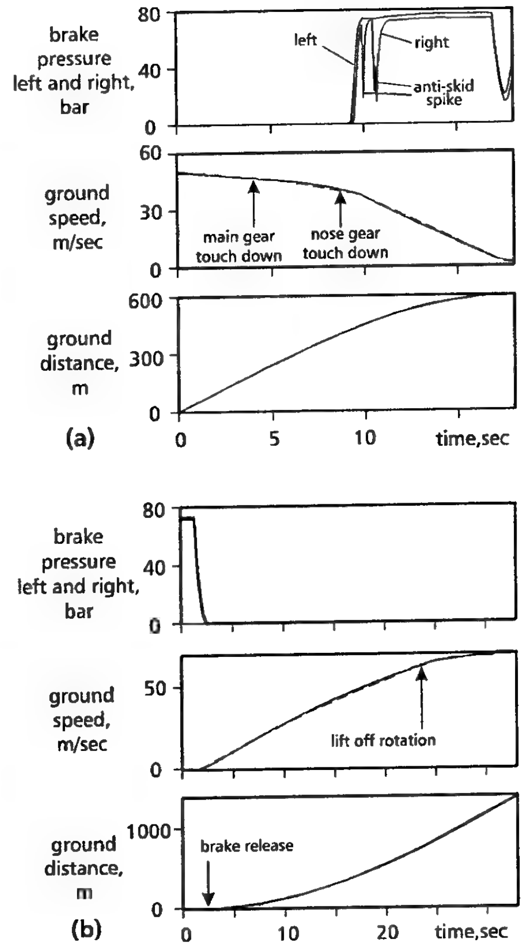

Fig. 5. Ground acceleration (a) and deceleration with brakes (b) validation, simulation model output (- - -) compared to taxi test data (——)

4. TIRE ACCELERATION AT TOUCH DOWN

Another example of C-160 ground handling model update is the aircraft derotation after main gear touch down. The measured longitudinal acceleration shows a considerable peak at main gear touch down, which originates from the force needed to accelerate the eight wheels of the main undercarriage (Fig. 6). In Fig. 6a this tire acceleration force is neglected in the simulation model, and a deficiency in pitch angle can be seen, which is violating the FAA Level D requirement for the pitch angle accuracy ($\pm1.5°$).

The computation of this force modifying the roll friction coefficient of eq. (3) is hard to realize, as the runway contact condition changes in a strongly nonlinear way from total slip to full adhesion. A simplified approach is adopted: the change of the aircraft's impulse at main gear touch down

$$\Delta I = m \cdot a_x \cdot t = F_{x,acc} \cdot t \tag{4}$$

can be computed, knowing the aircraft's mass and estimating the x-force $F_{x,acc}$ and the equivalent impulse time t using several measured time histories of the longitudinal acceleration a_x. For C-160, the equivalent impulse time was identified to app. 0.2 *sec*, the corresponding force for each of the ten wheels to $F_{x,acc} \approx 6,000\,N$. A ground speed dependency was neglected. Fig. 6b shows the simulation fidelity using this touch down impulse modeling. The fit of longitudinal acceleration and pitch angle is considerably improved and is now within the FAA Level D tolerances. The correct touch down point simulation of the main undercarriage can be seen, and even the nosewheel touch down after about 6 *sec* can be detected in both the measured and the computed acceleration. Furthermore, the touch down point is confirmed by the oleo compress plot of the main front gear. This oleo compress simulation, which is an important variable within the undercarriage force computation, shows an obvious improvement, too.

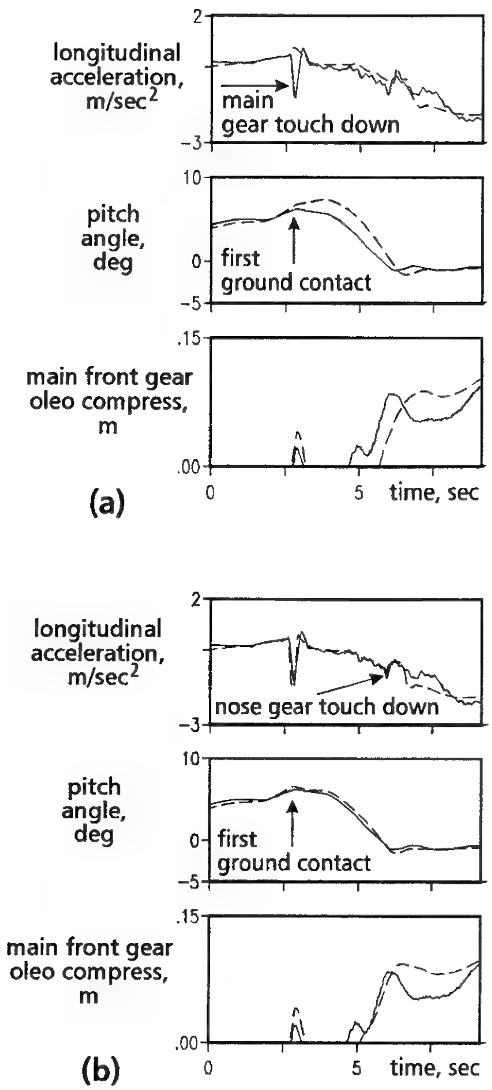

Fig. 6. Influence of tire acceleration on touchdown simulations: (a) neglecting tire acceleration, (b) modelling tire acceleration; model output (- - -), flight measured (——)

5. LATERAL DIRECTIONAL BEHAVIOR

At the beginning of the development process for a realistic lateral directional submodel, it is desirable to analyse the complex physics. The division into indispensable submodels (e.g. damper characteristics) and submodels, which are nice to have but not important for pilot's awareness, can reduce the complexity of the ground handling model structure noticeably.

Before trying to update the lateral tire characteristics with measured taxi test data, it is essential to model the geometry and kinematics of each landing gear precisely. This is important for the correct computation of the skid angle at each tire contact point to the runway. The skid angle is an essential input for the tire side force computation. As illustrated in Fig. 7 for the nosewheel, the skid angle τ is the difference between the steering angle η and the drift angle, that depends on the aircraft's yaw rate r and the location of the gear strut x_{CG}:

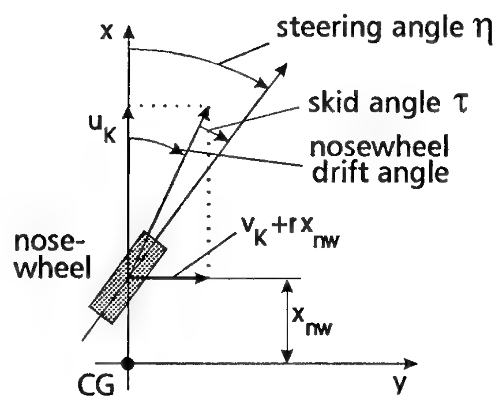

Fig. 7. Definition of the tire skid angle

$$\tau_{nw} = \eta - atan\left(\frac{v_K + r \cdot x_{nw}}{u_K}\right). \qquad (5)$$

The consideration of the yaw rate is important for the nose gear drift angle (considerable lever arm from the center of gravity to the gear contact point to the runway), but also for the main gear struts, although there are only small lever arms in the aircraft's x- and y-directions. Considering these lever arms, the skid angle at the main gear struts can be formulated:

$$\tau_{mw} = -atan\left(\frac{v_K + r \cdot x_{mw}}{u_K - r \cdot y_{mw}}\right). \qquad (6)$$

This exact formulation is important for simulation quality at low speed taxi [12].

After having described the kinematics precisely, the ground handling model can be updated with the identification results for the tire side force characteristics. Analytically derived 'deformation models' [11] are suitable, computer adapted formulations to describe the complicated nonlinear tire behavior in contact with the ground. These models consider not only the skid angle and the tire load, but also ground speed and runway and tire parameters. The tire parameters are often available for automobile and truck tires, but rarely for aircraft tires.

The taxi test data provide a lot of information about the aircraft's behavior at a certain runway condition, usually for dry concrete. Since the kinematic

variables can be computed from the onboard measurements, the tire parameters can be identified as a function of the tire skid angle using taxi tests with nosewheel steering angle inputs. It is essential that there are strong steering inputs at different ground speeds. Fig. 8 shows the identified side force as a function of the tire skid angle on dry concrete. For

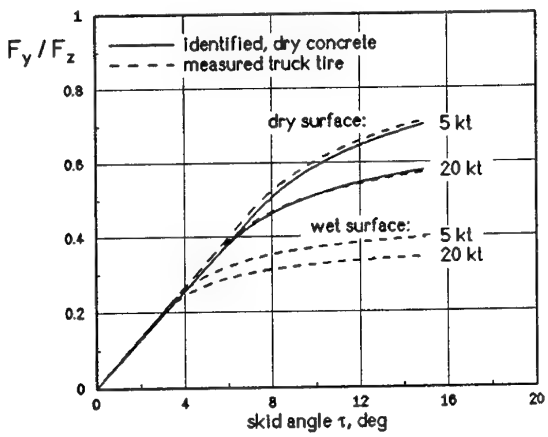

Fig. 8. Identified C-160 tire side force (F_y) characteristics on dry concrete; measured truck tire characteristics on dry and wet surface (constant normal force F_z)

comparison, the side force from the analytically derived C-160 model (using truck tire data) is plotted, too. On dry runway, there is a linear dependency up to 6° skid angle. For greater skid angles, there is no full adhesion anymore but partly slip and the side force is depending on the ground speed. Fig. 9 shows a typical rate of turn versus nosewheel angle proof-of-match plot on dry concrete using the identified side force characteristics. For wet runways, truck tires show similar linear characteristics for full adhesion (up to 4°) as on dry runways, but a considerable reduction of the maximal side force. Since the identified C-160 tire characteristics on dry concrete are very similar to the measured truck tire characteristics and since no C-160 test data were gathered for wet runways, the truck tire parameters are taken for taxi modeling on runways under adverse conditions (wet, icy, snowy).

Fig. 10 presents the lateral directional simulation quality with the complete C-160 simulator model for a typical normal takeoff from brake release up to 200 ft altitude. Directional control is maintained by the pilot by using the nosewheel steering and the rudder. These pilot control inputs are used directly as inputs for the simulation model, which was updated with the identified tire side force characteristics.

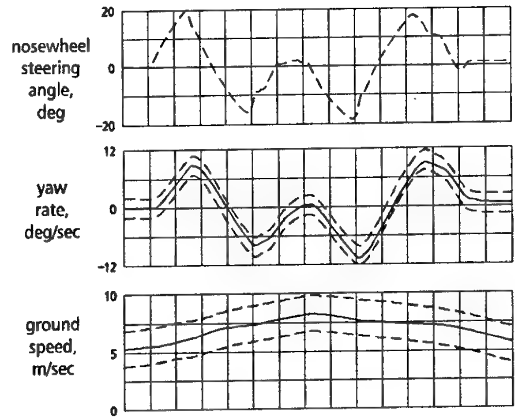

Fig. 9. Rate of turn versus nosewheel steering proof-of-match, simulation model output (——) compared to taxi test data ± FAA Level D tolerances (- - -)

6. BACKWARD TAXI

During C-160 taxi operations, it is possible to move the aircraft in backward direction by selecting a negative propeller blade angle. This backward taxi is

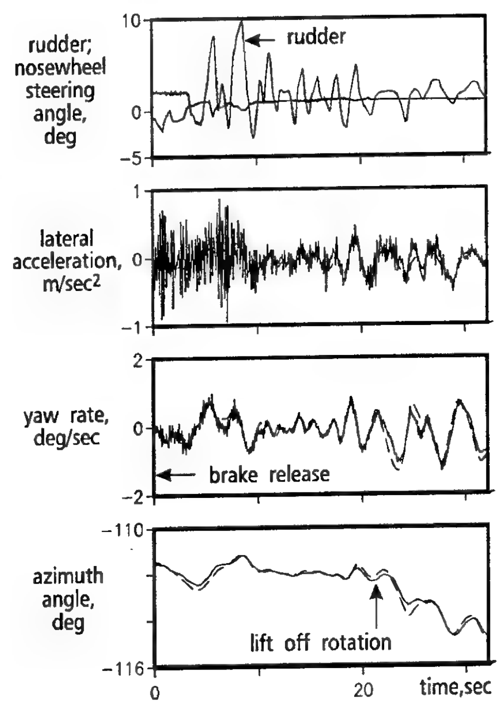

Fig. 10 Lateral directional control validation during normal takeoff, simulation model output (- - -) compared to flight test data (——)

not a FAA Level D required validation test, but for C-160 it was found to be desirable to have a valid simulator model for this operation.

For backward taxi, only minor changes in the ground handling model formalism were necessary. One point is the formulation of the friction coefficients (eq. (3)) depending on the aircraft's orientation and movement, as the friction always acts against the direction of movement. This can be modelled taking into account the sign of the x-component of the aircraft ground speed u_K. Eq. (3) is now:

$$\mu = (\mu_r + F_b \cdot p_b \cdot \mu_{b_{max}}) \cdot sign(u_K). \qquad (7)$$

As a second point, the nose wheel and main wheel skid angle computations of eqs. (5) and (6) have to be expanded:

$$\tau_{nw} = \eta \cdot sign(u_K) - atan\left(\frac{v_K + r \cdot x_{nw}}{|u_K|}\right) \qquad (8)$$

$$\tau_{mw} = -atan\left(\frac{v_K + r \cdot x_{mw}}{|u_K - r \cdot y_{mw}|}\right). \qquad (9)$$

In order to verify these modifications, Fig. 11 presents a backward taxi validation plot with three repetitions. For this validation simulation, the full 6-DOF model including engine and ground handling model was implemented. The lateral and longitudinal ground distance, which were provided by a laser tracker, are simulated very properly. Some additional signals, i.e. lateral acceleration, yaw rate, azimuth angle, and ground speed, show the simulation quality of the model.

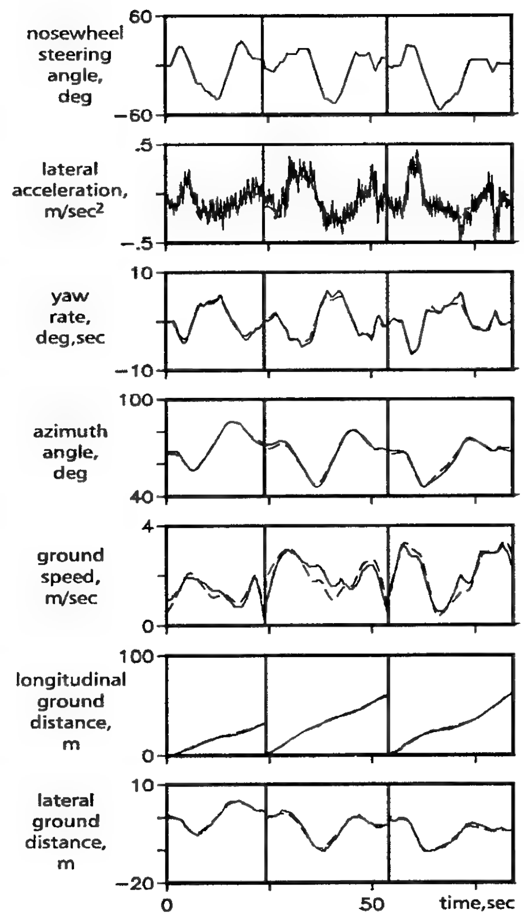

Fig. 11. Backward taxi validation (3 repetitions), simulation model output (- - -) compared to taxi test data (——)

7. LESSONS LEARNED

The examples of updating the C-160 ground handling model have clearly brought up the need for model validation. Nowadays, it is *not* the computer power, but it is a clearly arranged model structure, that determines the scope of the simulator math model. So a main task during the model development process is to find that model structure complexity, which obtains a predefined accuracy [1,13] in the most efficient way.

For ground handling models, it is a tough decision on how detailed the model has to be. It is clear that not all physical effects are noticeable for the pilot. The task is what amount of detail is needed in order to reproduce essential effects. The main criterion for establishing the necessity of modelling an effect should be, besides the level of accuracy, the *pilot's awareness*. In order to be independent of the pilot's opinion, flight (taxi) test data can support the decision on what is essential. Fig. 3 for example, presents the dynamic model of each gear suspension without the mass of the tire. This simplifies the differential equation for the tire axis altitude from 2nd order to 1st order. The validation of the model with flight test data and taxi test data proved that this causes hardly any reduction in model accuracy. The next step could be to neglect tire dynamics at all, probably the pilot would hardly notice it.

Another example is the consideration of the tire acceleration impulse (Fig. 6), which is very important for pilot acceptance. In this case, an *equivalent* model is used to describe the effect sufficiently, as the correct computation of the actual friction coefficient from total slip to full adhesion would require a huge data base. It is desirable to use those *equivalent* models, because they reduce the complexity and help to get a clear structure within the whole math model.

Especially for ground handling models, there is a strong need for the use and the determination of such equivalent models. As shown in this paper, system identification methods are capable of supporting a procedure, which can be split up into four steps:

- detection of model reduction possibilities,
- determination of *equivalent* submodels,
- identification or adjustment of model parameters using measured data, and
- model validation.

This procedure can be a powerful tool, not only for model development, but also for validation.

A simulator approval according to modern standards requires a lot of flight tests in order to show the model quality compared to measured data. The most convenient way to collect the additional data necessary for the development of a new model structure is to expand the taxi and flight validation tests.

8. CONCLUSIONS

This paper discusses some aspects of the development process of a ground handling model in order to achieve a predefined model accuracy in an efficient way. Taxi test data, which were gathered during the validation tests for a simulator approval, are evaluated with system identification methods in order to achieve a high quality model. Several examples for a C-160 ground handling model update are discussed.

Rolling and braking depend on the normal force and the corresponding friction coefficient. Evaluating differential braking taxi tests, two scale factors for the left and right brake pressures can be identified. The correct friction coefficients are validated with two typical validation tests: ground acceleration and deceleration after touch down using the brakes.

A correct modelling of the tire acceleration at touch down from total slip to full adhesion is difficult. As this effect is essential for pilot's awareness, an equivalent model is formulated, which uses the total acceleration impulse at each landing gear. Evaluating flight test data, the parameters of this model are identified and validated with landing impact flight test data.

Lateral directional behavior with ground contact depends on the tire side force model. An important part is the side force as a function of the tire skid angle, which can be determined using taxi test data with strong nosewheel steering inputs at different ground speeds. These identified characteristics are validated with lateral directional control test data during takeoff.

As a last example, it is discussed how to achieve a proper lateral control simulation quality during backward taxi. Changing the sign of the nosewheel steering angle and of the friction coefficients, and a modification of the tire skid angle computation are necessary to achieve a simulation fidelity according to FAA quality criterions for ground contact maneuvers.

Concluding, some aspects of effective ground handling modelling are discussed. It is essential to find an adequate level of model detailism, for which the criterion is - besides the required quality for approval - the pilot's awareness. A clearly structured model, which is easy to adapt to specific characteristics, can be achieved using equivalent models for complex physics. For determination of equivalent model parameters, system identification applied to taxi test data can be a proper tool.

9. ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support provided by the German Air Force, the German Procurement Organisation (BWB), and the German Air Force Flight Test Center WTD-61.

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TACTICAL ENVIRONMENT SERVERS

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SUMMARY

Mission training or evaluation on a manned military simulator requires the presence of friend and foe forces. These forces, either computer generated or man-controlled, must react in an intelligent manner, in real time. Due to restrictions in software tools and computing power (or manpower in the case of dedicated manned stations), as well as emphasis put on procedural and skill training more than on mission training, many existing simulators feature little or no tactical environment.

This paper presents a concept, the tactical environment server, which has been developed to populate the battle space of real time combat simulators with various computer generated friends and foes.

In the first part, tactical environment requirements for air combat and land battle simulators are discussed. Coherence between the server and its clients, one of the most problematic technical issues, is analysed.

A second part addresses the algorithmic and technological trade-offs one has to consider to implement a real-time tactical environment server. The connection of the server to the client simulator(s), via a network using the DIS protocol or via other solutions, is also discussed.

Implementation of a tactical environment servers for a Mirage 2000 and a combat helicopter simulator are presented and conclusions are drawn.

This project is sponsored by the Délégation Générale pour l'Armement (French MoD).

INTRODUCTION

Modern unpredictable and remote conflicts, advanced weapon systems and C3I, decreasing military budgets and environmental concerns are factors in favour of simulation-based mission training, which we define as training in the fulfilment of an operational mission in the presence of active forces. This training requires the presence of friend and foe forces, either computer generated or man-controlled, which act and react in a reasonably intelligent manner, in real time. These forces enhance the realism of the tactical environment and create the desired workload and stress which are associated with combat. Engineering simulators, used to design weapon system interface, also have to simulate the crew's workload in the most demanding phases of the battle.

Distributed Interactive Simulation promotes the creation of synthetic tactical environments through the connection of multiple simulations over remote, geographically distributed sites. Although the connection of manned simulators through wide area networks in Europe is technically possible, local computer generated forces (CGF) will be used to provide the required level of tactical realism to training or research and development simulators, whether they are new designs or legacy systems adapted for DIS connectivity.

This idea is the basis of the work that we have been conducting since 1991 on tactical environment servers, which has been funded in part by the Délégation Générale à l'Armement (French MoD).

WHAT IS A TACTICAL ENVIRONMENT SERVER ?

We will introduce this section by stating what it is not: it is neither a very accurate model for operational evaluation purposes, nor a constructive simulation. Potential problems of using constructive simulations in conjunction with manned virtual simulators are linked to their larger granularity (cycle time, terrain cells, size of units); they also require operators.

The tactical environment server is designed to be a plug-in unit requiring little or no human intervention during the exercise, easy to set-up, preferably from the IOS of the simulator to which it is connected. Implemented on a standard Unix workstation, its real time simulation models of friend and opposing forces are adapted to individual or crew training.

TACTICAL ENVIRONMENT

The natural and man-made environment is comprised of 4 domains:

- terrain,
- weather,
- electromagnetic,
- infrared.

In this synthetic battle space, computer generated entities evolve dynamically in interaction with the manned simulator(s). In addition, tactical events such as detonations occur.

Although our aim is to develop a common foundation for the simulation of air operations and land battle, tactical environment requirements are quite different for these two classes of simulation.

Simulation of Air Operations

Air operations which would most benefit of a tactical environment are :

- interception, where a friendly patrol seeks and fights enemy intruding aircraft,
- air police,

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- A/G strike, with multirole fighters or mixed aircraft,

- standoff A/G strike,

- reconnaissance.

Close air combat is not one of our design requirements, and is better practiced with networked manned simulators.

The trend in military training to include mission rehearsal capabilities in the requirements of mission simulators should be addressed. The link between mission preparation and the simulated tactical environment is tight in this context and will be taken into account for the design of future air operations tactical environment servers.

In the study we have conducted on tactical environment for combat aircraft simulators, we have focused on the challenging electromagnetic environment encountered by modern aircraft and created by radars and jammers of ground and airborne entities.

Adoption by the French Air Force and Navy of the AWACS and E2C may also increase the amount of C3I required in the tactical environment simulation.

Although modeling the electromagnetic environment does take into account the terrain, coherence requirements are not extremely stringent in this domain. It should also be stressed that the aesthetical correctness of tank motion (or whether it is moving at all) is quite irrelevant to a fighter aircraft.

Land Battle Simulation

Manned simulated platforms which are potential users of that class of tactical environment are tanks, armoured infantry vehicles, helicopters.

Simulation of the land battle usually involves:

- scores of opposing forces,

- coordinated friendlies,

- area effect weapons, such as artillery fire and mines.

This tactical environment is closely linked to the natural environment (terrain, objects, weather) and therefore coherence requirements with the manned simulator environment are strong.

CGF ENTITIES

Entity type

Mobile entities are characterized by the following sets of parameters:

- dynamic performance (performance of the platform expressed with 10+ parameters which include , for aircraft, minimum and maximum speed at sea level, mass, max positive and negative g load, max turn rate and so on),

- weapons system characteristics (radars, ECM, missiles and so on),

- behaviour rules.

Fixed weapon systems may be seen as mobile entities with the paradoxical characteristic of being immobile. A truck-mounted SAM site or a ZSU 23/4 exemplify that a distinction with the previous type is vain.

C3I entities are virtual entities that are necessary to model the tactical C3I system (for instance, the link between air defence units).

Entity behaviour

Entities exhibit at most two sets of behaviour rules (or "brains"):

- one set is dedicated to piloting the platform (for instance, the "pilot" is able to follow flight plans, avoid obstacles or follow a leading platform),

- the other set controls the weapons system including ECM and ECCM, gives orders to the "pilot", sends and receive tactical information (C3I interface).

Both "brains" have access to the environment through specialized server functions, such as height above terrain processing or radar processing.

High-order logical rules may be edited to define particular aspects of the behaviour.

TERRAIN AND TACTICAL DATABASES

Computer generated entities of the tactical server interpret natural and man-made environment at two levels of knowledge: the geometrical level and the tactical level. Interpretation at the geometrical level, which is the level usually fulfilled by the CIG in a manned simulator, uses files describing the geometry of the environment. This is used for the assessment of intervisibility between entities, CGF and remote, for computing altitude, height above terrain and for modeling physical interactions such as driving on the ground, landing, colliding, ...

At the tactical level, a description of the world, which is in our case an object-oriented database, feeds the decision processes such as route planning, hiding and combat.

The following objects are extracted from the terrain database:

- RIDGES and VALLEYS,

- WOODS,

- RIVERS,

- BRIDGES,

- BUILDINGS,

- TREES,

- ROADS.

Coherence between the manned simulator and its externally-generated tactical environment is a cruel necessity that has been particularly emphasized by the DIS community. Obviously, the geometrical and tactical databases must match as closely as possible the polygons that form the visual database of the manned simulator although this may not be practically achievable due to the levels of detail implemented for the CIG.

Terrain related functions have demanding requirements on coherence control: intervisibility, attitude and elevation of the computer generated entities relative to the terrain, collision avoidance (placement and existence of objects), road following.

Intervisibility

The process of assessing whether a synthetic actor is able to visually "see" another entity is very complex and does not yield a binary result. This decision is reached after successive stages:

- at the filtering stage, the relief of the terrain and the maximum detection range are used to compute the coarse geometrical visibility. This allows to conduct finer processing for a reduced number of entities.

- at the visibility stage, the overall visibility factor is computed based on background and foreground, and environmental conditions. The depth of scene analysis that is necessary to derive a fine intervisibility information could ultimately be close to the processing applied in a CIG.

- at the human modeling stage, physiological and psychological conditions of the simulated observer have to be taken into account with a set of deterministic (sensor characteristics, entity motion, visibility factor) and heuristic rules (random time to detection).

Terrain following

Since it cannot be expected that the terrain database used by the tactical server is exactly correlated with that of the manned simulator, the attitude and elevation of a computer generated land vehicle will generally look somewhat unrealistic to the crew of this simulator. Terrain following for ground vehicles can be achieved on the visual displays by requiring the CIG to clamp the vehicles to the ground although this introduces a discrepancy between their computed attitude and elevation (ground truth) and what is visually perceived by the crew.

SOFTWARE TECHNOLOGY: FROM AI to C++

Preliminary studies have been conducted on a SUN 3/160 workstation using LISP and the KEE environment from Intellicorp. Although these tools allowed to test and validate basic behaviour models and tactical databases, they would not allow for real-time performance. In the search for this goal, object oriented design and languages have been identified as more critical for these applications than AI techniques. We therefore switched to the C++ language and a CLASS RELATION based CASE tool. CLASS RELATION (Desfray 1994) is a full-fledged object model, based on the tight integration of three complementary models:

- the structure model describes application classes, their properties (methods, attributes, integrity constraints), the relation and inheritance diagram and the schema and domain-based structure,

- the operating model defines how classes are used, the object lifecycle, and the methods usage modes,

- the dynamic model describes the reactive behaviour of objects and the methods invocation dynamics. The CLASS RELATION method is industrialized by SOFTEAM through its CASE tool, OBJECTEERING

COUPLING THE TACTICAL SERVER: DISTRIBUTED INTERACTIVE SIMULATION (DIS) PROTOCOL

The DIS protocol was selected for this programme as the connection protocol with the manned simulator(s). Although no major problems have been encountered when implementing this protocol, there are a few domains not yet covered or unsatisfactory:

CGF initialization: Since there is at the moment no standard messages to initialize CGF with the DIS protocol, initialization of the entities is described by means of a text file.

Electromagnetic PDUs: the DIS protocol still needs improvement in the domain of electromagnetic interactions. PDUs do not cover the full range of interactions (Eg IFF) and must be trimmed.

C3I PDUs: the DIS protocol defines a Signal PDU but tactical messages have not been standardized. Some standardization for this type of messages has been established by NATO but not to the point of being easily interpreted by simulations and interoperability of simulations remains a long-term goal.

APPLICATIONS

MIRAGE 2000-5 Weapons system trainer

This trainer, under development, allows training in air combat and incorporates its own tactical environment server which provides for friendly aircraft, airborne targets and ground threats. It will be connectable through DIS with other trainers and simulators.

Land Battle Tactical Environment Server

A tactical environment server dedicated to a manned attack helicopter simulator is under development. The tactical environment features anti-tank helicopters, hostile attack helicopters, tanks and armoured SAM carriers.

This server will be connected to the TIGER simulator in operation at the Flight Test Centre in Istres, France.

Combat between helicopters will be simulated although restricted in a first stage to engagement with A/A missiles.

CONCLUSIONS

Our experiments with Land Battle applications have shown that our original goal of severely restricting human intervention during the course of the exercise is very difficult to achieve when, in some situations like hiding from an enemy in combat, computer generated forces will not escape from an unrealistically static position. In real life, orders would be expected from the higher echelon or actions would be inferred from subjective reasons rather than from doctrine. A complaint of the users we did not expected was that the computer generated enemies were sometimes too smart and a degradation in combat performance was subsequently introduced.

The key word to user acceptance of computer generated forces is then flexibility, in the preparation and the execution of the exercise.

In the preparation of the exercise, not only the type, number and mission of the entities but also their behaviour must be definable. It must be possible to assign subjective behaviour attributes to units such as morale and proficiency, allowing the simulated crew to choose between conflicting rules (protect your life and equipment vs destroy opposing forces).

During the exercise, we plan to give to the instructor the possibility to enter new mission orders and to take control at any time of a computer generated entity (Eg, fly an enemy aircraft).

Further developments we plan to conduct for aircraft simulation applications are related to the C3I environment.

Modern combat aircraft such as the Rafale feature sophisticated tactical displays fed by data links and are tightly integrated in a tactical network (in that case, the SCCOA) which plays an essential part in the preparation of the mission and in its execution. The tactical environment server must generate the interface between the aircraft simulator and the C3I entities and it must have the capability to use the output of the mission preparation systems or to reproduce their functionality.

We plan to study the simulation of tactical data links, airborne radar systems and to extend the capabilities of the tactical environment server in the mission preparation and rehearsal domain.

UK Attack Helicopter Flying Qualities: The Role of Piloted Simulation Evaluation in Supporting the Procurement Decision Making Process

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Summary:

Contenders for the UK Army's Attack Helicopter (AH) competition, were subjected to a Technical Assessment during the period November 1993 to December 1994. The Defence Research Agency's Flight Dynamics and Simulation Department were Lead Assessors for the flight control system and handling qualities aspects of the assessments. FDS carried out a programme of off-line and piloted simulation activities in support of the handling qualities assessments, using the DRA's HELISIM simulation model. A piloted simulation evaluation was completed using the DRA's Advanced Flight Simulator, where the objective was to evaluate the contenders handling qualities and agility in the context of the AH mission. The paper describes the test techniques and procedures used in the tests and discusses the background details of the handling qualities assessment methodology. Some conclusions are also drawn regarding the effectiveness of simulation in supporting defence procurement objectives, and potential future developments.

Presented at AGARD FVP Symposium 'Flight simulation: Where are the challenges?', Braunschweig, Germany, 22-25May 1995.

1. Introduction

In 1991 a Staff Target (ST) was raised for an Attack Helicopter (AH) for the British Army to be procured 'off the shelf' on a competitive basis. In this context, off the shelf meant that the UK MoD would not fund a separate development contract and did not intend to be the first user of the aircraft system. Hence, it was important to determine exactly what was being offered by prospective bidders, to assess potential shortfalls against the targets and to identify areas of risk. To this end, the MoD AH Project Office initiated a technical assessment of candidate aircraft against the Staff Target. While much of the assessment was expected to be based on expert opinion, whenever possible assessors were tasked to provide independent estimates for compliance checking and validation purposes, either by analytical means or simulation modelling. One important area was the relative agility of the contending aircraft and the flying qualities necessary to underpin the aircraft's mission effectiveness.

Flight Dynamics and Simulation Department (FDS) of the Defence Research Agency were lead assessors for the flight control system and flying qualities aspects of the UKAH. In consultation with the Project Office, FDS planned a coordinated programme of off-line and real time, piloted simulation activities to support the assessments. Piloted simulation evaluations of the

AH contenders were subsequently carried out at the DRA's Advanced Fight Simulation (AFS) facility at Bedford, using the Large Motion Simulator (LMS). This was the first time in the UK that such an exercise had been carried out to support a major procurement activity. The test techniques and evaluation procedures were drawn from previous FDS experience of research associated with new handling qualities criteria, such as those related to the US Army's Aeronautical Design Standard for the RAH-66, ADS-33 (Ref 1).

This paper discusses the background to the assessments, the FDS approach to handling qualities evaluations, and the aims, test procedures and results achieved in the piloted simulation trial. The paper also addresses simulation fidelity and validation issues and the lessons learned. **In the interests of commercial confidentiality, only general results are given and there are no references or inferences to any particular aircraft.**

2. Background and overview to UKAH Assessment

The UKAH Staff Target described the attributes of the weapon system that the Army required together with the primary mission details and desired performance in the form of a Cardinal Points Specification (CPS). The UK MoD's Procurement Executive was tasked with identifying suitable equipment which might be available on the world market and assessing it in terms of cost effectiveness against the CPS. The technical aspects of the assessment were carried out with the assistance of almost 100 specialists drawn mainly from the Defence Research Agency.

In terms of timescale, it took eighteen months from the time of the formation of the Project Office to the issue of an Invitation To Tender (ITT) to the bidders. During this time, assessment teams were formed and briefed, who then assisted in compiling a Technical Data Requirements list (TDRL) as part of the ITT. The TDRL comprised nearly 700 target parameters required by the ST together with over 2000 back up items of data. Bidders were required to return their proposals within nine months and assessors were subsequently allowed five months in which to complete an initial appraisal of the TDRL data. During this time, they raised any necessary points of clarification and requested any vital information which appeared to be missing.

The ITT was issued to five prospective bidders and one additional unsolicited bid was received. One of the major difficulties faced by the Project Office was the different developmental status of the contenders. At the time of receipt of the Tenders, none of the aircraft existed in the form in which they were offered; the scale of difference varied from a design concept, through an aircraft which had recently completed its first flight to aircraft being substantially updated from the models currently in service. In many areas this was not necessarily a problem because the bidders could provide sufficient data on which to base a risk assessment. Regarding the flying qualities aspect, in view of the aircraft's need for an all-weather capability (supported by sophisticated visual aids), it was considered to be high risk to rely solely on a 'paper' assessment and hence, that the bids be subjected to a more thorough evaluation. As the lead assessor for the flight control system and handling qualities, FDS was tasked with this undertaking.

As noted above, the flying qualities of the contenders were evaluated through various simulation activities, of which the focal point was a piloted simulation evaluation using the AFS. Other elements included an off-line assessment of each contender against the flying qualities criteria specified in Aeronautical Design Standard ADS33 (Ref 1), the latest US specification for handling qualities of military rotorcraft, using a specifically developed software 'Toolbox' (Ref 2). The handling qualities Toolbox derives ADS-33 criteria based on inputs from test data or from the responses of the imbedded HELISIM simulation model. In another activity, inverse simulation techniques using the Glasgow University/DRA HELINV model (Ref 3), were used to predict the performance capabilities and control workload of each contender in AH related mission tasks.

The viability of the evaluations was critically dependent on the quality of the data provided by the bidders through the TRDL. FDS had specified

a number of TDRL requirements that were intended to elicit key data sets for building HELINV and HELISIM configurations, and appropriate flight or model data for calibrating the DRA model responses. In the event, the data provided were adequate on both counts and enabled satisfactory models to be constructed to meet the aims of the evaluation plan.

3. Flying Qualities assessment methodology

Good flying qualities underpin mission effectiveness and flight safety. Establishing flying quality requires a combination of quantitative criteria, that define the customer's best understanding at a given time, and subjective opinion of how well the aircraft is fit for purpose. At the time of writing, the available quality standards for helicopter flying qualities are reasonably comprehensive. However, existing criteria relate to single axis response characteristics and pilots rarely fly single axis tasks when conducting a nap-of-the-Earth mission. A thorough test of quality therefore requires evaluation in task; the interplay between quantitative criteria and pilot subjective opinion of task-worth characterises the DRA approach to flying qualities assessment, and its application to the UKAH, as outlined below.

3.1 Flying Qualities Synergy and the ADS-33 Standard - A Resume

The DRA approach to flying qualities evaluation is based on the concept that flying qualities represent the synergy between the internal attributes of the vehicle - its stability and control characteristics, cockpit ergonomics etc., and the external factors that influence the piloting task - threat level, atmospheric disturbances, quality of visual cues etc. Implicit in this approach is the assumption that flying qualities are task-oriented as reflected in the new standard, ADS - 33D (Ref 1), anchored in a unique test database derived from advanced simulation studies and in-flight validation studies over the last 15 years. ADS-33 is formally a US Army standard for the RAH-66 helicopter, but has been developed out of International Collaboration and, in its structure and form, is applicable to all roles and types. The framework for using ADS - 33 as a requirements capture, design and evaluation methodology is illustrated in Fig 1, developed from Key (Ref 4). The detailed response type requirements follow from the user-defined missions and operational environments, and hence the usable cue environment (UCE). Resultant handling qualities levels are judged on a combination of results from clinical open-loop and demonstration closed-loop test manoeuvres.

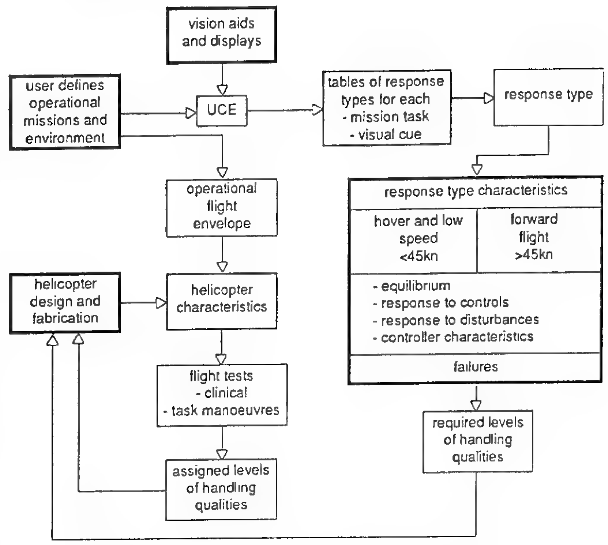

Fig 1 ADS-33 requirements capture, design & evaluation Methodology

Any helicopter designed to the ADS- 33 standard should exhibit very good qualities; formally the ADS-33 standard states that a helicopter should exhibit level 1 qualities (desired performance consistently achievable at low pilot workload) throughout the operational flight envelope. In this sense the standard has to be seen in the context of high levels of flight control augmentation, that tame the natural tendencies typified by the lack of carefree handling, strong cross couplings and poor stability. The question then arises as to what value is ADS-33 in judging the capabilities of existing aircraft or, more generally, aircraft not designed to this Standard? This question is particularly relevant to the UKAH evaluation. Research experience to date suggests that most current operational helicopters exhibit a wide range of Level 2 characteristics combined with some Level 1 and even Level 3 characteristics. A Level 2 helicopter can still perform missions with adequate performance but the pilot is likely to

have to work much harder to compensate for deficiencies. The ADS-33 standard has been developed to discern flying quality across all three Levels, and hence is properly applicable to existing aircraft as well as super-augmented aircraft of the future, in both normal and failed conditions (where some degradation into Level 2 and 3 is allowed). Indeed, much of the database used in the development of ADS-33 from current types was used to substantiate the new criteria in the Level 2 region. One of the outstanding issues in all flying qualities work relates to the effects of a combination of Level 2 characteristics on pilot workload and task performance and the uncertainty surrounding these effects is perhaps the single most important reason for the continued strong emphasis on the need for pilot subjective evaluation in mission tasks.

ADS-33 states that, "*Compliance with the requirements will be demonstrated using analysis, simulation and flight test...*" This places initial emphasis on capability demonstration during design, through analysis and simulation. Confidence in the results of compliance demonstration in design is critically dependent on the simulation fidelity level, including modelling and cueing environment. For the UKAH evaluations, it was important that any limitations caused by simulation infidelity were well understood. Modelling issues are discussed briefly in Section 4.2, but even with perfect aircraft modelling there is still a question over whether tests conducted in ground-based simulation can accurately predict flying qualities levels.

A review paper by Condon (Ref 5) presents data showing the extent to which ground-based simulation has improved during the 1980s. During the formative years on ADS-33, in the early 1980s, there was a clear disparity between ground-based simulation and flight test data (Ref 6). Pilots were not able to achieve Level 1 handling qualities with rate command response types in simulation, while the flight data predicted a genuine Level 1/2 boundary. Problems were attributed to poor visual and motion cueing in the simulation and the ground-based data were discounted. When the DRA's AFS became available with a large motion capability in the early 1990s, one of the first tasks was to establish

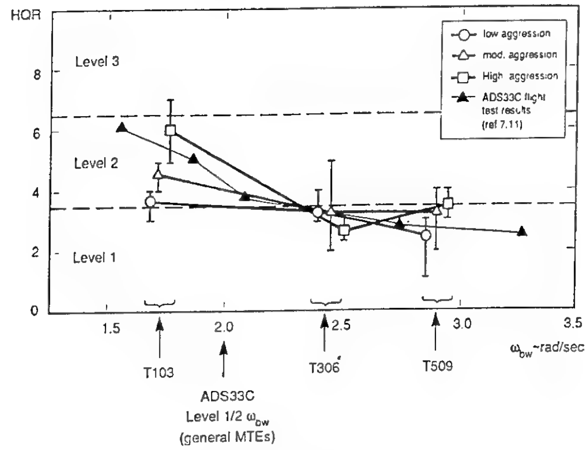

Fig 2 AFS Sidestep handling qualities results versus ADS-33 flight test data

the degree of conformity with the ADS-33 flight test data. Fig 2 presents roll axis handling qualities results for rate command response type aircraft flown in a sidestep mission task element (Ref 7). The key handling qualities parameter relating to closed-loop piloting is the attitude bandwidth, defined conceptually as the highest frequency that the pilot can close a task loop without threatening stability (Ref 1). The ground-based simulation data are shown compared with the ADS-33 flight test data, indicating very good correlation with the Level 1/2 boundary predicted at a roll axis bandwidth of about 2.5 rad/sec - about 25% higher than the, more conservative, ADS boundary itself. The AFS data also confirmed the importance of motion cueing to pilot control strategy, acting as a realistic filter to 'high gain' activity on the one hand and suppressing the over-controlling typical without motion, especially in the vertical axis (Ref 7).

The substantiating evidence of good fidelity, coupled with the engineering experience with flight and simulation trials over many years, made the AFS an ideal tool for evaluating the UKAH contenders flying qualities, relative to the ADS-33 standard. Two guidelines were established. First, in general, it would be expected that the simulated aircraft would be marginally more difficult to fly than the real aircraft. Second, that the quality of the phototextured visual scenes and motion cueing were expected to be sufficiently realistic to expose any potential pilot - induced - oscillations, which can threaten flight safety at the higher levels of task aggression.

3.2 The 3 - Stage Evaluation Methodology

The approach taken by DRA can be described under three headings as follows:

(i) clinical tests and the HQ toolbox analysis; The ADS-33 standard contains a set of criteria for different response types and different control axes (Fig 1). These response characteristics are further subdivided into criteria for different ranges of frequency and amplitude. For example, agility characteristics are represented by large amplitude (control power) and moderate amplitude (quickness) criteria, while stability characteristics are represented by long term open-loop (e.g. phugoid, Dutch roll damping) and short term closed-loop (bandwidth) criteria. Quality criteria for the different forms of cross-coupling are also defined. These criteria are typically formed into 2 - parameter diagrams with defined boundaries between Level 1, 2 and 3 quality standards. The DRA handling qualities toolbox (Ref 2) has been developed to derive these parameters from flight or simulation test data and to present results automatically on the HQ charts. The DRA Helisim model is an integral part of the Toolbox, and pre-defined or custom test control inputs can be applied to the simulation model to produce responses from which the HQ parameters can be derived. The HQ Toolbox is developed within the MATLAB/SIMULINK environment. Areas of particular interest in the UKAH evaluation were agility, stability and cross coupling. Evaluations were made with and without stability and control augmentation.

(ii) inverse simulation; The Glasgow University/DRA inverse simulation approach integrated into the software package HELINV (Ref 3) was used to predict the limits to agility in MTEs. HELINV takes as input the MTE, defined in terms of flight path kinematics, along with aircraft limits, e.g. control, power. The HELINV algorithm effectively inverts the simulation model to compute the rotor loads and hence controls required to fly the manoeuvre. Some validation of this approach has been conducted with Lynx flying slalom MTEs (Ref 8), where comparison between flight test and HELINV results indicated that control limits were reached at very similar levels of agility, at a slalom aspect ratio of about 11%.

(iii) pilot in-the-loop simulation using the AFS; This element of the methodology forms the main topic of this paper of course and will be discussed in more detail in later Sections. Underpinning the piloted evaluation is a well defined series of mission task elements or flight test manoeuvres with well defined desired and adequate performance levels. These need to be (clinically) representative of operational situations, reflecting in the present case the UKAH role. Pilots need to be able to perceive accurately their achieved task performance, dictating careful design of the MTE visual cueing. Pilots also need to be familiar with the roles being considered and properly trained in the use of the Cooper-Harper Handling Qualities Rating (HQR) scale (Ref 9). The latter is particularly important for achieving consistency between pilots regarding the interpretation of low, moderate and considerable levels of compensation, for example. Finally, HQRs need to be arrived at following structured dialogue between the trials engineer and test pilot, that serves to document the reasons for the HQR.

The three - stage approach contains a number of synergistic features. The Toolbox analysis can focus attention on areas of apparent serious deficiency while the HELINV results can identify limiting conditions to support the design of the MTEs. In the next Section, the approach to and results from the AFS trials are described in more detail.

4. UKAH AFS simulations - the approach

4.1 AFS trial objectives

The overall objective of the FDS assessment strategy was to evaluate the contenders flying qualities and to check that these would not unduly constrain the levels of 'useable' agility, in the context of the AH's primary mission. The AH will be required to operate in the battlefield environment, primarily flying anti-armour, ground suppression and anti-helicopter missions. For mission effectiveness, it was stipulated in the target operating characteristics that "...The AH should have handling and engine response qualities appropriate to accurate flight path control with low pilot workload in the NOE, battlefield environment. Suitable means should be provided to

allow for exploitation of the full flight envelope when flying 'eyes out' without the risk of inadvertent and unacceptable excursions beyond it....". In addition, a number of key point performance characteristics for given flight states were also defined, which specified the desired acceleration and speed capabilities for the aircraft. Taking the two issues together, it is implicit that the aircraft should embody good agility and manoeuvrability coupled with handling qualities that allow the pilot to exploit the available performance, with confidence and safety.

The specific aim of the AFS trial was to check the pilot in-the-loop flying qualities, levels of workload, task performance and agility for each of the contenders, and to provide important data for comparison with inputs from the off-line simulation predictions. Specifically, the objective of the trial was to conduct piloted evaluations of the contenders' handling qualities in mission-orientated tasks extracted from key flight phases of the AH's primary anti-armour role.

4.2 Simulation Models - Creation and Validation

Simulation models of the UKAH contenders were created based on the data provided in the TDRL responses from bidders. Currently there are three versions of the generic DRA HELISIM, distinguished largely by the complexity of rotor modelling. The hi-fidelity version employs an aeroelastic rotor model with non-linear unsteady aerodynamics and is currently undergoing integration into the real-time AFS environment. The Helisim version adopted for the HQ Toolbox and HELINV analysis employs a rigid-blade disc approximation, with dynamic multi-blade coordinate representations of blade coning and cyclic flapping motion; blade aerodynamics are linear (Ref 10). For the real-time simulation, the rotor blade degrees of freedom were further approximated by quasi-steady representations of flapping and coning. This level of approximation is known to give moderate levels of fidelity across a frequency range between zero and about 10 rad/sec, in terms of primary axis control response, in the absence of aerodynamic nonlinearities e.g. caused by interactional effects or rapid manoeuvring. Comparisons with the test data provided by the AH bidders confirmed this. The linearity assumptions also become increasingly fragile a high speeds, but, since only low - mid speed MTEs were flown, this weakness was not considered to have a significant impact on the results.

One of the known failings of a flap-only model with simple 3-component inflow modelling is the poor fidelity of cross coupled pitch/roll responses and the HELISIM versions of the UKAH contenders were no exception. Comparisons varied from poor to fair and the general approach taken during the off-line analysis and piloted simulations was to reduce the emphasis on the cross coupling quality criteria. During the piloted trials, particular care was taken to identify any adverse comments relating to a characteristic that was known to be poorly modelled. In the event, none of these areas appeared to be critical to the test pilots, who were encouraged to give emphasis to the primary control response (agility) and stability characteristics.

Rotorspeed was assumed contant for all configurations. HELISIM does feature a generic powerplant/rotorspeed governor/fuel flow model, but insufficient data were provided to model the different configurations. Constant rotorspeed will on the one hand obscure any handling features relating to delayed engine response or torque overshoots; also, the instantaneous engine response is likely to result in less representative yaw coupling. Any pilot comments relating to these issues were noted, as with pitch to roll couplings, although, once again, they did not appear as a major driver to the HQRs.

Configurations were modelled together with the stabilisation components of the stability and control and autopilot augmentation systems, again using data supplied by the manufacturers. Autopilot modes were excluded since all the MTEs evaluated were essentially full attention active flying tasks.

Overall, correlation with the test data provided by the bidders showed adequate correlation for primary response characteristics in terms of control power and damping. This conclusion is

supported by previous validation work conducted using HELISIM with Lynx, Bo105 and Puma flight data. As noted above, cross coupling was, in general, poorly modelled, although the levels were such that, in a broad sense, similar handling qualities would be expected between model and the real aircraft, e.g. Level 2 handling qualities for pitch/roll/pitch coupling described in terms of the ratio of off-axis to on-axis response span the wide range from 25 to 60 % in ADS-33.

4.3 Test and evaluation methods

The test and evaluation procedures used for the AFS assessments were based on well tried and robust techniques, developed during previous FDS handling qualities research (Refs 7,11,12,13) through the complementary use of the ground based AFS and Lynx/Puma airborne test facilities. From previous experience, notwithstanding the limits of simulation capability, it was considered that the results would provide a valuable insight into the contenders primary axis handling characteristics to complement the HELINV and Toolbox analyses. Moreover, given the importance of motion cueing for piloted handling qualities evaluations, the AFS with its Large Motion System (LMS) was considered to be well suited for the AH assessments.

The AFS configuration, test procedures and test manoeuvres are discussed in more detail below.

4.3.1 Simulator Configuration

The available time and resources precluded a detailed representation of each aircraft's cockpit, controls, cockpit systems and displays. Each contender was evaluated in a 'standard' configuration, with the assumption that they would be equally affected by any deficiencies.

The simulator configuration used in each case featured a single-seat helicopter cockpit with a Lynx seat and controls and a 'standard' set of head-down flight instruments. Visual scene content was displayed via a Link-Miles Computer Generated Imagery (CGI) visual system and three cockpit mounted monitors, arranged to provide one centre and two side windows. 'Platform' motion cueing was provided by the LMS. Key features are summarised below.

<u>General</u>

Specific features include:

- Electric feel-system with Lynx mechanical controls (centre-stick, rudder pedals and collective)

- Lynx seat featuring vibration cueing scheduled with airspeed and normal 'g'

- Link Miles Image 600-PT visuals featuring 3 windows with maximum field of view:

  - Total azimuth: +/- 63deg,
  - Centre window vertical: +/- 18deg
  - Side windows vertical: +/- 24deg

- LMS motion cueing: Maximum accelerations including -

  - Vertical: +/- 1g
  - Lateral/Longitudinal: +/- 0.5g
  - Angular: +/-2 rad/s^2 pitch, 3 rad/s^2 roll, 1.5 rad/s^2 yaw

- Head down display of primary flight instruments, e.g. artificial horizon, airspeed indicator, normal 'g' meter, main rotor speed and engine torque indicator

- Data logging facilities:

  - automatic recording of pilots control activity, aircraft responses and flight path coordinates via computer disk and pen chart recorders

  - video records of pilot's eye-view from the centre window

<u>Controls configuration</u>

Where possible, the controls were configured as friction devices or with static force gradients and breakout characteristics using information supplied by the bidders. Alternatively, the controls were configured with Level 1 characteristics in accordance with Def Stan 00-970 (Ref 14) and

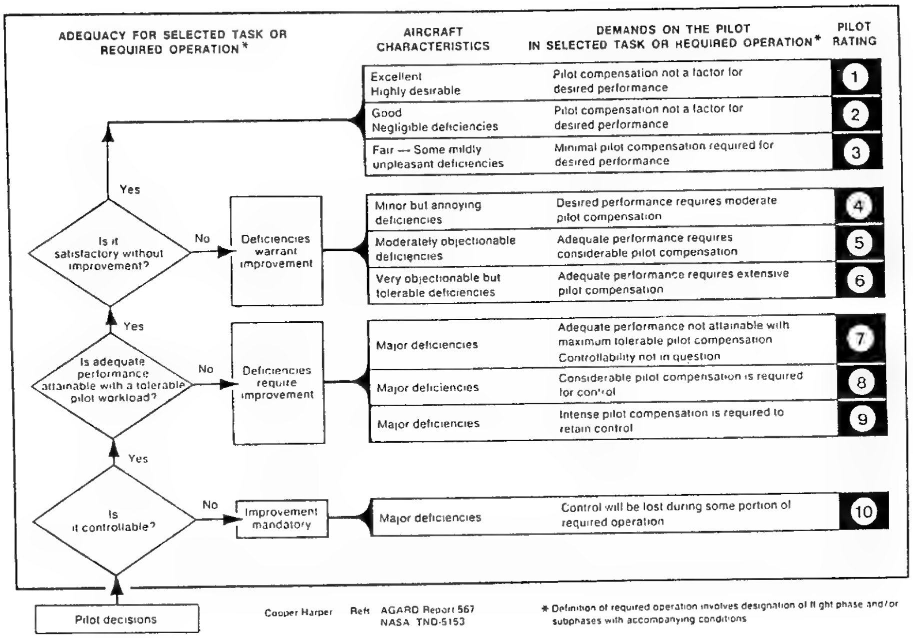

Fig 3 Cooper-Harper rating scale for handling qualities

ADS33C criteria. Regarding dynamic characteristics (frequency, damping and inertia), for the centre-stick and rudder pedals data representing measurements from a Lynx were used. The rudder pedals and collective controls had trim force release buttons, positioned on the collective control grip, while the cyclic control had trim follow-up and trim release buttons, mounted on the hand grip. These functions were not considered to be part of the assessment and were generally only used when setting up trim conditions.

Simulation transport delays

With the CGI visual system, the total system latency, ie. time between initiation of a control input and visual system response, has a mean of 115ms +/- 10ms. The latency is an important factor in handling qualities evaluations because it directly influences the minimum achievable phase delay and maximum bandwidth that can be modelled. However, checks on attitude bandwidth using the handling qualities Tool-box indicate that, when compared to the predicted data for the contenders, the AFS latency would not have a significant impact on the validity of the evaluations.

4.3.2 Test procedures

To meet the assessment objectives, test pilots evaluated the contenders' handling qualities in a set of mission-related flight tasks, or 'mission task elements' (MTE). MTEs form the basis for 'stylised' tasks specifically designed to enable formal handling qualities evaluations using the Cooper-Harper rating scale (Ref 9), shown in Fig 3. To help confirm pilot impression and to enable them to review the handling qualities in a total mission context, pilots were also required to fly a simulated AH mini-mission. In this task, pilots had to complete an NOE flying sequence, interspersed with discrete mission task elements, in order to accomplish a number of mission objectives, eg. target acquisition, general reconnaissance. For the formal evaluations, the pilots were required to achieve the tasks within given accuracy constraints and special visual cue arrangements were used to assist the pilot in judging the level of task performance achieved. Pilots were also required to

evaluate the tasks at different levels of aggression, where aggression refers to pilot control strategy and may be taken as an indication of how hard the pilot is 'driving' the aircraft, or the level of inherent aircraft performance that is exploited in the execution of the task. Experience has shown (see Refs 11-13) that testing over an increasing range of aggression can expose potential handling qualities 'cliff-edges', which signify a rapid rise in workload as the pilot strives to maintain adequate task performance under increasing time pressures. Hence, the intention was that pilots should explore the effect of task aggression on task performance, workload and agility in their handling assessments.

In order to achieve a reasonable consensus, evaluations were completed by three different pilots, who were each allowed three sorties in which to assess each contender. The first sortie was allocated to training and familiarisation and the following two for formal evaluations. Before assigning a rating, the evaluation pilot was allowed to practise the task until a consistent level of task performance had been attained; the on-line data logging was used to provide feed-back information to the pilot on applied levels of task aggression and task performance achievement. Handling qualities ratings were recorded using the Cooper-Harper 'decision tree' and scale and, in addition, a special questionnaire was used to record supporting comment and opinion. Pilot's control demands, flight path coordinates and vehicle responses were also logged for all designated evaluation runs and subsequently used to confirm achieved levels of task aggression and task performance. At the end of each sortie, pilots completed a further questionnaire as a means of providing a more detailed debriefing on their ratings and assessments. They were also asked to complete a summary report on their overall impression of each configuration, based on their experience in flying the simulated mission.

4.3.3 Test Manoeuvres

From ADS33C, a mission task element or MTE, is defined as "...An element of a mission that can be treated as a handling qualities task...". For the AH evaluations, MTEs were selected on the basis of the primary mission profile and the piloting tasks associated with key phases of the mission. In its primary role, the AH will typically be expected to spend a high proportion of time in NOE flight, at speeds below 80kn, and in manoeuvring at low speed close to the hover. As an agile combat helicopter, it must be capable of delivering rapid and accurate control of flight path. To this end, the speed and precision with which the pilot can redirect the rotor thrust, through control of attitude, will be a major factor. Hence, the roll axis response characteristics, and to lesser extent those of the pitch axis, play a key role in determining the suitability of the aircraft's handling qualities for the role.

The MTEs chosen for the evaluations included two hover and low speed tasks, the lateral sidestep and the quickhop, and one forward flight task, referred to as 'lateral jinking'. These MTEs had been developed and tested in previous FDS research (Refs 11,12) and through participation in the European collaborative programme on ACT for rotorcraft (Ref 13). They represent handling qualities evaluation tasks with well defined control strategies and manoeuvre objectives, and with clear performance goals and levels of task aggression. Handling qualities in the tasks are dominated by the primary roll or pitch axis response characteristics, where key parameters will be roll/pitch controllability (control power and sensitivity), roll/pitch attitude quickness and closed-loop stability (attitude bandwidth and phase delay)

The sidestep and quickhop are essentially hover re-positioning manoeuvres (see Figs 5 & 6), which might entail moving from one point of cover to another with minimum exposure time, or perhaps a move from cover to complete an observation task. The sidestep task is dominated by the roll axis response, but at the same time a multi-axis control strategy is needed to coordinate the heading (rudder pedals), height (collective) and track over the ground (longitudinal and lateral cyclic). In handling terms, the sidestep is characterised by three distinct phases; an initial roll to accelerate the aircraft, followed by a roll reversal to decelerate and a final roll out to stop and re-establish a hover. In the same way, the quickhop features a pitch down, pitch reversal and pitch down phases associated with accelerating and stopping the aircraft.

Table 1: MTE task performance requirements

MTE	MTE Phase	Heading/ balance - deg -	Height - ft -	Ground track - m -	Over/ under shoot - m -	Plan position - m -	Speed - kn -
Sidestep	Transition	+/- 15 D +/- 25 A	> 5 D > 10 A	+/- 3 D +/- 6 A	+/- 3 D +/- 6 A	na	na
	Terminal hover	+/- 5 D +/- 10A	+/- 5 D +/- 10 A	na	na	+/- 1.5 D +/- 3 A	na
Quickhop	Transition	+/- 15 D +/- 20 A	> 58 D > 65 A	+/- 3 D	+/- 10 D +/- 15 A	na	na
	Terminal hover	+/- 3 D +/- 6 A	+/- 5 D +/- 10 A	na	na	+/- 3 D +/- 6 A	na
Lateral jinking	Overall	+/- 5 D +/-10 A	+/- 2.5 D +/- 5 A	na	na	na	+/- 5 D +/- 7.5A
	Tracking	+/- 5 D +/-10 A	+/- 2.5 D +/- 5 A	+/- 3 D +/- 6 A	+/- 3 D +/- 6 A	na	+/- 5 D +/- 7.5A

Table 2: MTE task aggression requirements

MTE	Aggression parameter	Level of Aggression		
		Low	Moderate	High
Sidestep	Net roll attitude change during accel/decel	8-12 deg	18-22 deg	28-32 deg
Quickhop	Net pitch attitude change during accel/decel	8-12 deg	18-22 deg	28-32 deg
Lateral jinking	Maximum roll attitude during the 'jink'	10-20 deg	25-30 deg	40-50 deg

Table 3: AH Simulated mission sequence

Element	Location	Objective
1	Centre of farmyard	Hover at 25ft AGL, spot turn & transition to river bed
2	Northwards along river bed	Follow river bed maintaining height 25-30ft & speed 30-50kn
3	First village	Enter village, decelerate to hover and spot turn to reconnoitre buildings
4	First thicket on right bank of river	Return to NOE flight following river - Rapidly decelerate to hover within cover of trees
5	- ditto -	Execute bob-up to reconnoitre church, followed by bob-down to cover
6	- ditto -	Execute sidestep to right to reconnoitre surrounding terrain and return to cover
7	Northwards along river bed	Execute rapid sidestep to left from cover, turn rapidly & resume NOE flight following river
8	Second village, right bank of river	Rapidly decelerate to hover within cover of building
9	- ditto -	Execute bob-up to reconnoitre church & and bob-down to cover; bob-up to acquire & track building
10	- ditto -	Turn & make rapid withdrawal along the river bed (70-80kn).

Lateral jinking (see Fig 7) is essentially a roll axis slalom manoeuvre, combined with sequences of tracking elements, and is designed to test the capability for accurate control of flight path in low level NOE flight, in the presence of obstacles in the ground plane. The test objective is to check lateral/directional handling qualities in transient turning manoeuvres in the mid-speed range and in acquiring and maintaining a designated track. Again, in handling terms, the task is characterised by an initial roll in followed by a roll reversal to achieve the flight path re-alignment, and then a roll out to acquire and hold the tracking line. The manoeuvre is dominated by the primary axis roll responses, but again a multi-axis control strategy is required for maintenance of height, speed and balance.

Task performance and aggression requirements are defined in Tables 1 & 2. Regarding task performance, note that where appropriate, different requirements are given for 'desired' and 'adequate' levels. The target levels of task aggression were specified through an appropriate parameter associated with the primary control axis; for a sidestep for example, aggression is specified in terms of the maximum roll attitudes to be achieved during the acceleration and deceleration phases of the manoeuvre. The three levels are also indicative of the maximum angular rates, attitudes and translational rates to be achieved during the manoeuvre. In relation to the AH mission, the intention was that 'low' aggression represents unhurried or cautious manoeuvring in the presence of threats, or perhaps manoeuvring in poor visibility or confined places etc. Similarly, 'moderate' represents manoeuvring with 'normal' levels of mission urgency where there may be no direct or imminent threats, while 'high' represents rapid weapon deployment, direct threat avoidance/evasion, or rapid withdrawal from danger zone.

As noted above, pilots were also required to fly a simulated AH mini-mission as part of the assessment. The mission sequence was flown after the MTE tests and although not formally evaluated, it gave the pilots a final opportunity to review their impression of the handling qualities in a broader range of mission tasks. The general mission plan and sequence of events are summarised in Table 3. A representative view of the CGI scene detail for the NOE database is shown in Fig 4.

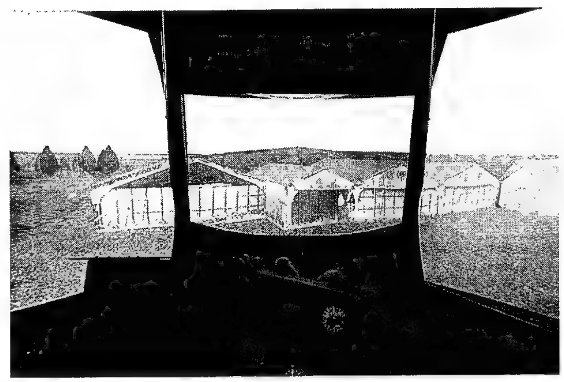

Fig 4 NOE scene detail

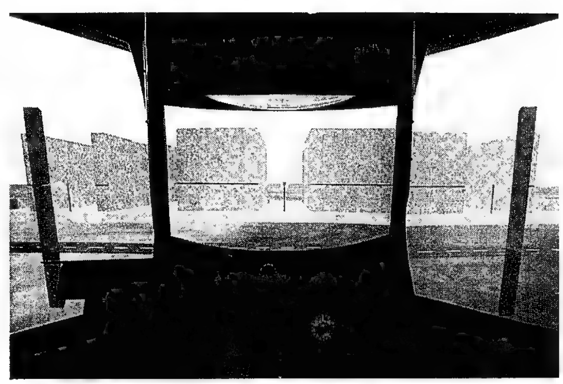

Fig 5 Sidestep MTE

4.3.4 CGI Task cue arrangements

Referring to Fig 5, for the sidestep the principal cues are provided by a building-like structure and sighting arrangement. The near and far sights are designed to give height and plan position error feed-back relative to the 5/10ft (desired/adequate) requirement. The road in the foreground is

intended to give additional longitudinal position cueing during the lateral translation. The posts provide additional height and longitudinal position cueing for precision hovering.

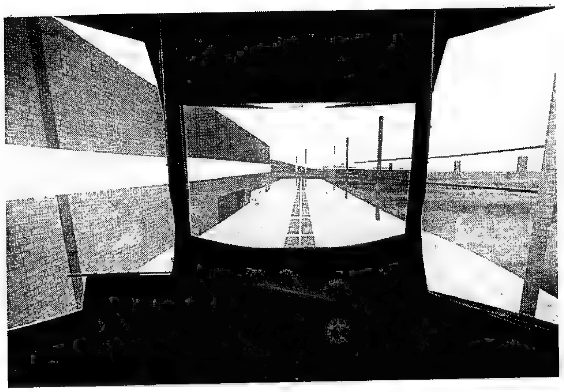

Fig 6 Quickhop MTE

Task cues for the quickhop are shown in Fig 6. Height and position cueing are given by a road running between a building and a gantry- like structure. The building window line shows the target task height and its upper extremity delineates the desired task performance range. The initial and final hover positions are given by adjacent vertical black lines on the wall and the gantry, which for correct positioning should be aligned in the centre of the side windows. The road edges provide lateral positioning information. The vertical posts in the forward field-of-view are placed to give height and track cues during the final 'flare'.

For lateral jinking, see Fig 7, the task layout consists of a sequence of turning gates located on either side of a roadway. The gates are represented by sets of four posts, comprising a small inner pair, which represent adequate tracking performance (12m wide), and a larger outer pair which serve as a height reference. The direction of the roadway defines the tracking lines, while its width (6m wide) defines the desired tracking performance.

5. UKAH simulations - the results

The principal test objectives as discussed in the previous section were met. Sufficient information was provided by the bidders for building simulation model configurations and the calibration exercise gave confidence that the model responses were acceptable for the piloted simulation test objectives. Results achieved in the subsequent simulation evaluations were consistent with the findings of previous FDS flight control related research and were also in good agreement with the off-line assessments using the handling qualities Tool-box. In particular, pilots comments and ratings were well matched with predicted handling qualities levels for roll and pitch axis bandwidth, attitude quickness and control power criteria.

Handling qualities evaluations were carried out by three pilots at moderate levels of task aggression, where in all cases either desired or adequate task performance requirements were achieved. The tasks were also attempted at higher aggression levels and in nearly all cases, the pilots were able to achieve at least adequate performance levels. Most important, pilot comment showed that, generally speaking, simulation constraints did not unduly influence their perception of handling qualities. One formal set of evaluations at high aggression was carried out and the results are presented below, together with those for moderate aggression. Some general comments on the overall results are also given.

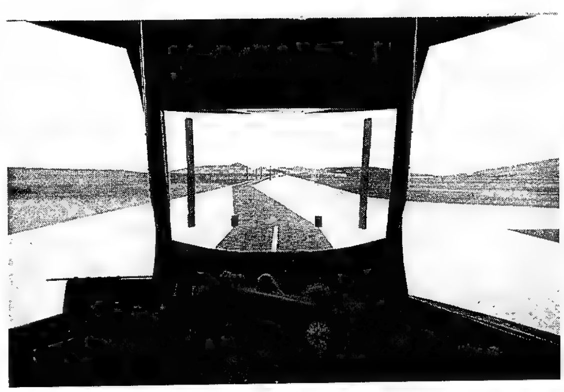

Fig 7 Lateral jinking MTE

5.1 Pilot ratings

A summary of pilots ratings for handling qualities is shown in Fig 8. The plot shows the mean and spread of ratings for each configuration, for the three evaluation tasks.

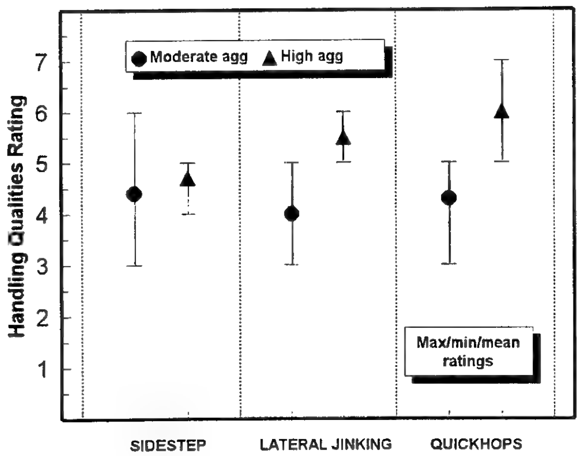

Fig 8 Pilots ratings for handling qualities

For moderate aggression, the spread of ratings was generally within one scale point, indicating a good consensus of opinion between the pilots. In three instances scatter increased to 1.5 or 2 scale points, and in one of these cases, ratings also crossed the Level 1-2 rating boundary. The variation may be explained by differences in control strategy and task aggression. Within the targeted task aggression, at low to moderate levels, the pilot can use significantly lower roll rates to achieve the change in roll attitude, as indicated by lower attitude quickness (Ref 7). This may reflect choice of a more relaxed control strategy, or may result from poor handling qualities, where the pilot is using a strategy that reduces the need for excessive compensation. Also, from observation, application of aggression tended to be a function of pilot background, ie. experienced 'attack' helicopter pilots tended to achieve higher attitude quickness values when compared with transport helicopter pilots.

Ratings for the high aggression case show a clear increase in mean rating compared to the moderate aggression results. Such results reflect the need for a sample of different subject pilots and to test across a range of task aggression. As aggression increases, the combination of task performance demand and increasing time pressures on the pilot reduce the scope for 'backing-off' on control demand. As noted above, testing across a range of aggression can give evidence of a handling qualities 'cliff-edge'.

5.2 Pilot comments and opinion

From pilot comment, for the tasks evaluated simulation related limitations/deficiencies were not considered to be unduly intrusive, and were generally judged not to have had a significant impact on the results. A representative comment from one pilot was that:

"... The AFS provided a good method of comparison of the three aircraft. Some simulation limitations detracted from the overall realism but probably had little effect on the results achieved. The visual system was limited at high pitch up attitudes which precluded conducting truly representative tactical manoeuvres, however the required level of aggression was achieved in the assessments. The motion system gave good cues for most tasks, but when manoeuvring aggressively the lateral and yaw cues became unrepresentative..."

As commented, field-of-view limitations in the quickhop task were probably the most noteworthy limitation, and may have given rise to an estimated degradation in ratings of 1 scale point at the moderate level of aggression. At higher aggression, motion cueing was noticeably more intrusive, although pilots still preferred to fly with the motion system engaged. From past experience, tasks flown at high aggression in fixed-base simulations tend to give rise to pilot disorientation and even nausea. This is particularly true for NOE tasks which involve dynamic roll axis manoeuvring such as lateral jinking.

The head-down instrumentation was reported to be generally too far from the pilots normal scan to provide more than minimal assistance, particularly in high aggression tasks. Regarding torque margins, at the target levels of task aggression, pilots were mostly able to achieve the task within the desired margin, particularly for the lateral jinking task which was evaluated at a speed close to the minimum power case. However, for the low

speed tasks at higher levels of aggression, when manoeuvre attitudes exceeded 25deg, there was a noted tendency to exceed the defined limit.

There were no adverse comments regarding the cockpit inceptors. Where used, the Lynx controls breakout forces and gradients were considered to be satisfactory, and there were no reported handling qualities deficiencies due to control characteristics.

6. Future challenges

6.1 Future applications

The direct use of handling qualities simulations during an aircraft procurement has been a novel and successful experience. For a competitive selection process such as the UKAH, the AFS was demonstrated to be a valuable tool for assessment of handling qualities, whereby it allowed piloted evaluation of representative aircraft models in an even environment against predetermined objectives. The ability to compare results against other areas of the technical assessments increased confidence in the overall level of credibility. Although actual flight evaluation of current models of the contending aircraft was undertaken, these activities were regarded very much as complimentary to the simulation activity, with different primary objectives for each. However, it is important to note that in common areas, the findings from the piloted simulation were consistent with those for the aircraft evaluations.

Following the successful completion of the AH assessments, it is of interest to review the potential role of simulation in future procurement activities, both from a general standpoint and in association with the chosen AH. Reviewing a typical procurement process, there are three key follow-on phases where support might be considered. Firstly, following contract award, for 'acceptance off contract' there is a need to check the 'deliverable' against the agreed performance specification. Secondly, for an aircraft it is then necessary to establish flight envelope limits for mandatory airworthiness requirements and for in-service use of the aircraft. Finally, in parallel with the other activities, it is essential to assess the aircraft for potential modifications and upgrades which might be needed, either to address shortfalls in current operational capability, or to ensure continued effectiveness throughout its service life. Such activities will usually entail an extensive trials and evaluation programme to provide the necessary substantiation data. For an 'off-the-shelf' buy, while existing test data (supplied by the contractor) may already be available, further testing will almost certainly be required.

From a Project Office perspective, accomplishing test plans in a timely and cost effective manner is a key issue. Flight testing is an expensive and sometimes 'risky' business, and simulation can potentially help to improve the cost effectiveness and safety of the evaluation process. For example, simulation can be used to increase the productivity of flight trials by identifying and directing attention to safety critical conditions within the flight envelope. Simulation allows flight up to and beyond flight envelope limits to be explored, without the attendant flight safety risks. Again, simulation can provide a flexible tool for preliminary assessment of airframe or flight control system modifications, eg. airframe mass re-distribution (ie. addition to or variation of weapon load), or an AFCS modification, for impact on handling qualities. The capability for assessing flight in degraded visual conditions is another important application of simulation, and facilities like the AFS are regarded as essential tools for the development and testing of helmet mounted displays (HMD). From a research standpoint, simulation provides an important resource for investigation of technologies and concepts that might be exploited in a mid-life update, the application of Active Control Technology (ACT) being a prime example.

For the potential to be fulfilled, it is important that the issue of simulation fidelity is addressed. From the 'customers' standpoint, there is a need to define adequate levels of fidelity in relation to specific simulation objectives, and to specify the substantiation criteria that will be needed. In view of the ongoing requirement, it is important that there is a development strategy for facilities like the AFS that will provide the desired capability.

6.2 Simulation requirements

For future applications, to meet the customers needs, it would be clearly advantageous to be able conduct evaluations in specific mission environments and operational scenarios. Regarding battlefield helicopter roles, operation in the DVE is a high risk area for handling qualities requirements and hence it is considered that there is a particular need to achieve a high fidelity simulation of the helicopter and its visual aids/displays in the DVE. Such a simulation would serve as a cost effective tool to support generic research into visual system development, assessment and compliance testing of future projects. This set of research is currently receiving attention in a pan-DRA activity funded by the MOD's Applied Research Programme.

Key elements of a high fidelity simulation include models of the aircraft and its mission systems, including the ability to represent two crew operations, the natural environment, including visual scene and effects of wind and turbulence, and the operational scenario, including modelling of threats. The AFS has demonstrated its capability for supporting fundamental rotary wing handling qualities research over the past four years and more recently, it has demonstrated the capability for supporting work on visually coupled systems (VCS) for DVE operations. At other sites within the DRA, there simulation facilities which already provide sophisticated mission simulation capabilities. Hence, for the future, the AFS may best be adapted to meet the customers needs through 'networking' to run parallel simulations with those facilities.

6.3 Facility configuration

Generally speaking, the AFS is well suited for the type of assessment programme that was carried out for the AH. The facility will be subject to upgrades programmed throughout its life that will enhance its capability to meet the requirements discussed in the previous section. The main elements of the simulation and the potential influence on handling qualities are discussed in the following paragraphs.

Visual system:

For evaluation of handling qualities in NOE flight, where flying is essentially 'eyes out' of the cockpit, it is important to achieve a good representation of the outside visual scene. The outside visual cues provide the pilot with the information needed for accurate flight path control, and will have a critical impact on the ability to adopt a realistic control strategy; poor or missing cues will almost certainly demand some degree of pilot compensation which will serve to spoil the impression of handling qualities. Hence, factors such as the available Field-of-view (FOV) and the representation of fine detail and textural cues can have a critical influence in piloted handling qualities evaluations (Ref 15). Similarly, where there is a requirement to simulate DVE conditions, the fidelity of the visual environment model will be of primary concern. For features such as fog and ambient light modelling, there is the problem of defining the cueing requirements and levels of fidelity needed to achieve an adequate simulation.

In addition to FOV, the issue of scene detail also needs to be addressed. The resolution provided by typical visual systems is best suited for forward flight and improvements are needed for helicopter low speed flight in the NOE. The problem is most accute for very low speed tasks close to the hover, particularly when high precision is needed, eg. positioning or weapons aiming tasks. To put this into perspective, pilots have reported that in real NOE flight, they use details such as the movement and aspect of blades of grass for information regarding relative wind direction, speed over the ground and flight path direction. To some extent, especially for transient manoeuvring cases, the situation can be improved by adopting task designs such as those used in the AH assessments. Here, the objective is to enrich the visual scene with patterns of objects, which, as the vehicle moves even slowly, serve to create a discrete 'flow field' effect, from which relative translational rate and positioning cues may be perceived.

Cockpit, pilots controls and instruments

For mission simulations for a two seat aircraft like the AH, as noted above, it should be possible to

simulate 2 crew operations through networking. For the pilot station, from a handling qualities standpoint, it will be important to provide suitable inceptors and flight instruments. The inceptors dynamic and static force displacement and trimming characteristics can have a significant impact on pilot impression of handling qualities. Hence, it is important that they are adequately represented in the simulation.

As a source of primary cueing information for piloting control, cockpit instrumentation is another important factor in handling qualities evaluations. For helicopters, the need to observe critical flight envelope limits such as normal 'g', rotor torque and RPM serves as a primary source of workload; audio and tactile warning devices are sometimes available to provide some degree of 'carefree handling'. Hence, missing or poorly positioned instruments can also serve to spoil otherwise satisfactory handling qualities.

'G' Seat, Sound & vibration cueing

Sound and vibration cues not only serve to create a more realistic impression in a simulation, but they are an important source of secondary cues for vehicle flight state. The amplitude and frequency of sound and vibration in helicopters are generally strongly modulated by flight condition. When the pilot is flying eyes-out, such cues are used by the pilot as indicators of potential rotor under/overspeed or over-torque situations, and large normal 'g' loads. Hence, they can be a contributory factor in reducing pilot workload.

Motion cueing

The principal function of motion cueing is to provide cues of the onset of acceleration through stimulation of the body's motion sensory mechanisms (Ref 16). From Ref 17, motion cues are important for handling qualities simulations concerning aircraft with marginal stability, high gain tracking tasks and flight in disturbed conditions. The AFS' provides both platform motion and pseudo-motion through a G-seat.

The so-called 'G' seat provides the onset of normal 'g' cueing that the pilot would normally feel through 'the seat of the pants'. In transient manoeuvre situations, onset of 'g' is an important indicator of aircraft flight state and has a primary influence on pilot control strategy. For a pilot in-the-loop control task, normal 'g' provides a feed-back loop by which the pilot judges and moderates the strength and progress of the flight path response. From Ref 18, missing cues can give rise to over-controlling and increased workload and use of a 'G' seat can help to recover the situation.

From Ref 19, fixed-wing research has shown the importance of motion cueing in achieving the necessary fidelity to simulate high gain, pilot control tasks. showing that motion was needed to in order to capture pilot-induced-oscillation characteristics (PIO). Similar results have also been reported for helicopter simulations, see Refs 7. In this case, it was concluded that pilots have a tendency to fly more aggressively with no motion cueing due to the missing acceleration cues. There was also evidence that the increased aggression gave rise to significant over-controlling. For the heave axis, it was found that lack of motion cues gave rise to a PIO tendency in tasks that demanded accurate control of height.

System latency

As noted above, system latency is an important factor in simulating handling qualities because it can limit the minimum phase delays and maximum bandwidth that can be achieved. Latency is associated with the computing time delays in converting pilot's control demands into simulator cue demands and responses at the cockpit. In a real aircraft, the achievable attitude bandwidth is influenced by time lags associated with the actuation, flight control and rotor system characteristics. For aircraft with high speed rotors, basic system time delays in the roll axis can be as low as 50ms, while helicopters with slower rotors, lags can be greater than 100ms. For an aircraft with full authority ACT, additional time delays can be expected, depending on the computational efficiency of the system. The ADS-33 bandwidth criteria reflect the predicted deterioration in handling qualities due to increasing time delays. As noted in Section 3 of the paper, the current AFS configuration is adequate for predicting the Level 1/2 handling qualities boundary for rate command helicopters; in these experiments, as

with the UKAH trials, the time delays from the physical elements of the aircraft were effectively simulated by the AFS system delays.

6.3 Simulation model

Regarding the simulation model, there are several known areas of flying qualities deficiency that are currently not modelled adequately by the Helisim model, and hence will not have been addressed in the assessments. In the low speed MTEs, the influence of the main rotor wake on the tail rotor and empennage can have a significant effect on the pilot's ability to hold a steady flight condition and perform accurate flight path control. The extent of this effect varies considerably from type to type, depending largely upon the development work carried out by the manufacturer. A second example concerns the effects of blade stall on manoeuvrability at mid-high speeds. Performance in tasks requiring accurate flight path control and attitude tracking could be degraded depending on the extent of this problem. No conclusions can be drawn about potential problems in these areas as a result of the FDS flying qualities evaluations. Hi-fidelity modelling developments planned for the AFS over the next few years will provide the capability to examine such areas.

7 Conclusions

This paper has described the approach taken to the assessment of the flying qualities of the UKAH contenders, with particular emphasis on the piloted simulation element. The approach has demonstrated the complementary capabilities of off-line evaluations, using the ADS-33 Handling Qualities toolbox and inverse simulation, and piloted tests to establish flying quality. The background to the UKAH project and the overall evaluation programme have been summarised, followed by a résume of the DRA approach to flying qualities assessment. Simulation models of the contenders were assembled, within the DRA Helisim framework, from data provided by the bidders. The simulation facility used for the piloted evaluations, the Advanced Flight Simulator, and the associated experimental design have been described in some detail. Three test pilots conducted the evaluations in three mission related tasks - the sidestep, lateral jinking and quickhop - followed by a UKAH mini-mission, assembled as a series of contiguous tasks. Flying at moderate levels of aggressiveness, the pilots were able to complete all the tasks within adequate performance standards for all configurations flown. Confidence in the results was increased by the low spread of pilot handling qualities ratings and the overall pilot impressions that the simulation was representative for the tasks flown. Research also correlated well with off-line Toolbox and HELINV analyses.

Simulator limitations encountered during the trial did not seriously detract from the objectives nor compromise the conclusions drawn, but were noted and have provided the focus for technical discussion on fidelity requirements for handling investigations in this paper.

Specific points are as follows;

(i) the combination of visual, motion, audio and tactile cues work synergistically to give the pilot a realistic impression of flying.

(ii) visual cues provide the most compelling inputs to pilots controlling a helicopter's flight path and attitude in the NoE. The field of view of the CGI display in the AFS helicopter cockpit was adequate for most of the MTE flying, giving strong periphal cueing laterally, but the range in the vertical FoV limited the level of aggressiveness possible in pitch manoeuvres. Textural detail, provided by the CGI photo-texturing, proved vital for good low speed velocity and attitude cues and was supplemented by a range of artificial objects to assist pilots judge desired and adequate levels of task performance.

(iii) motion cues provide the pilot with important lead information, in general working to contain control aggressiveness to realistic levels and also proving vital to the correct prediction of PIO boundaries. In the UKAH trials, motion cues proved effective. At high levels of aggressiveness, control strategy became affected by spurious cueing, particularly in the roll/sway axes. Work is in hand to improve the motion drive laws in this area.

(iv) the design of a piloted simulation trial can be guided to great effect by off-line analysis as demonstrated in the DRA's approach to the UKAH assessment. Conducting analysis of a helicopter's response characteristics à la ADS-33 gives a clear indication of a helicopter's strengths and weaknesses. Effective use of the HQ Toolbox and HELINV inverse simulation has been made in this context to focus attention during the piloted evaluations.

In this, first of a kind, exercise in the UK, much valuable information has been captured to assist in the overall assessment of the competing weapon systems and the DRA approach to flying qualities evaluation has proved successful in providing insight into the mission capability of the UKAH contenders. Piloted simulation has demonstrated its worth in highlighting handling characteristics relevant to the UKAH role. This assessment has also provided the opportunity to identify areas where simulation fidelity needs improvement to realise the full potential in supporting design, evaluation and, ultimately, airworthiness certification.

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THE USE OF PILOTED SIMULATION FOR CIVIL TILTROTOR INTEGRATED COCKPIT DESIGN

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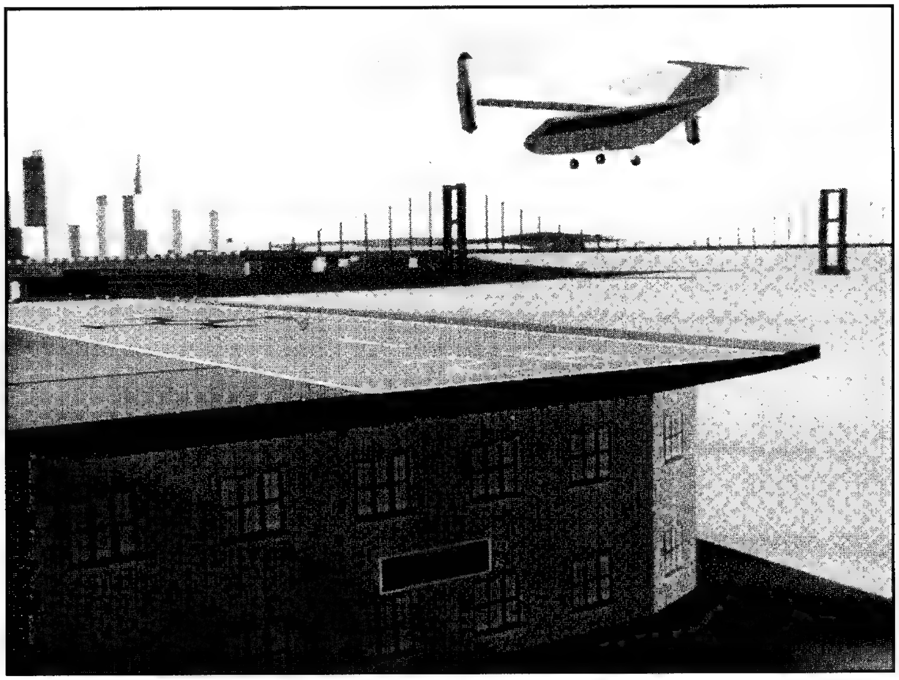
Ground-based flight simulators are receiving increased use in the design of civil aircraft. In addition to traditional simulation roles in support of cockpit control and display design, simulators are now used to develop new flight procedures and to assist in airport design. This is particularly true for the concept of a civil tiltrotor transport. This presentation summarizes recent simulation activity at NASA's Ames Research Center focused on the design requirements for the introduction of tiltrotor aircraft as economic vertical flight transports.

Paper presented at the AGARD FVP Symposium on "Flight Simulation — Where are the Challenges?", held in Braunschweig, Germany, from 22-25 May 1995, and published in CP-577.

Presentation Outline

- Introduction
- Experiment
  - Facility
  - Design/Conduct
- Results
  - Controls
  - Displays
  - Procedures
  - Infrastructure
- Conclusions

This presentation will begin by discussing the motivation and background for the civil tiltrotor simulation investigations. This will be followed by a description of the simulation facility and the experimental design for a series of experiments. The results discussion will range from traditional simulation roles of control and display development through the new application for civil aircraft operation of terminal area procedure development and airport design.



CTR on Approach to SFV

The successful flight demonstration of the tiltrotor aircraft concept by the XV-15 and its subsequent development for the U.S. military in the V-22, Osprey, program suggest the potential for a civil tiltrotor transport operating from "vertiports" located near transportation market centers.

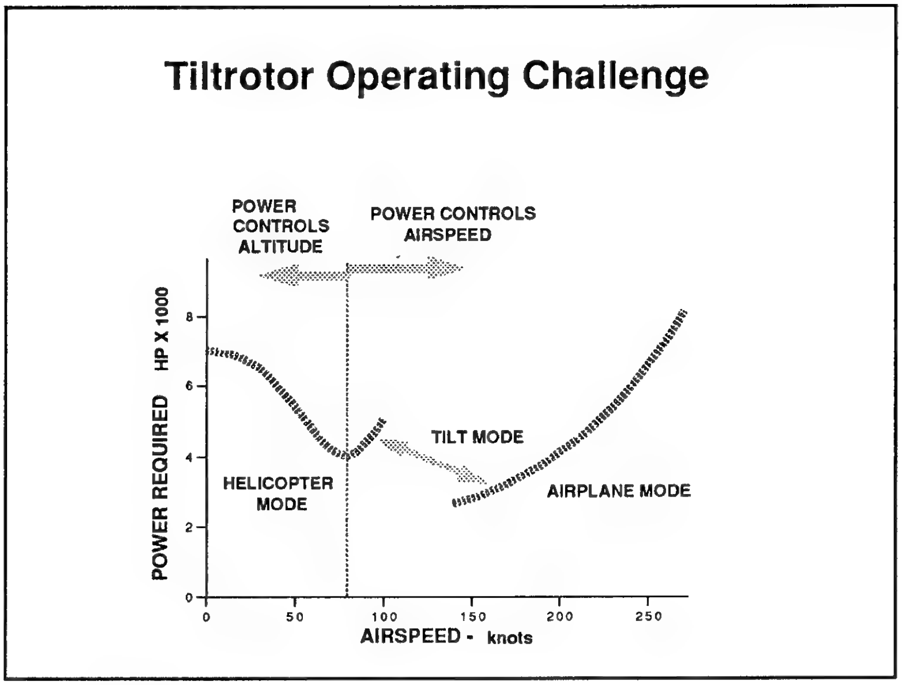
Motivation for Civil Tiltrotor Investigations

- **NASA-FAA-Industry studies show potential civil tiltrotor market.**
- **Certification and operations criteria required for this new class of powered-lift aircraft.**
- **Define infrastructure requirements:**
  - **Vertiport**
  - **Air Traffic Control**

Market studies have identified such a market as well as technical, economic and political issues to be resolved.

Building upon an interim powered-lift aircraft certification criteria, both the U.S. FAA and European certification authorities have begun a review of those criteria as their application to an aircraft becomes more real.

In the course of the aircraft design and operations criteria review, design guidelines for the ground facilities (vertiports) and operating procedures are also reviewed and commented upon.



The tiltrotor operating challenge is exemplified by the power-required curve, shown here as a function of airspeed and flight mode. A tiltrotor aircraft has a series of power curves based on nacelle angle (rotor orientation). These extend from airplane mode through the tiltrotor's unique "tilt" mode back to slow-speed operation in helicopter mode. These curves show both the performance potential of an airplane that can operate as a helicopter and an airplane and everything in between. They also help illustrate the operating challenge presented to the pilot. At higher speed forward flight, the pilot principally controls altitude or flight path angle with pitch attitude. As the aircraft slows down, the pilot shifts control strategy to use power as the principal flight path or altitude control. Through a series of simulation investigations, we have seen this "backside" of the power curve operation requires cockpit aids for precise operations such as steep glide slope tracking.

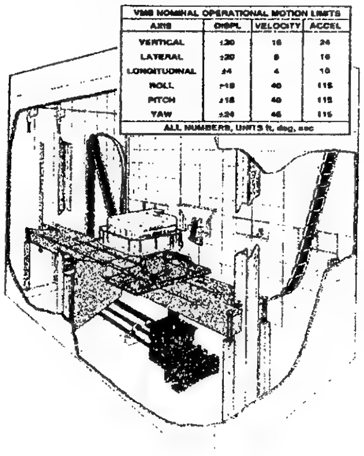
Civil Tiltrotor Experiments

- **CTR-1: Conversion location**
- **CTR-2: Raw data guidance on steep approaches**
- **CTR-3: Flight Director and Flight Path Vector Displays on steep approaches**
- **CTR-4: Terminal operating procedure development**
- **CTR-5: One Engine Inoperative Operations**

To date, a series of five major piloted simulation experiments at NASA's Ames Research Center have investigated various topics important to cockpit design and terminal area operation of a civil tiltrotor transport. The first experiment investigated where during the approach to convert from airplane mode to helicopter mode--in level flight or on glide slope. The second and third experiments investigated cockpit guidance requirements for operation on steep instrument approaches. The most recent experiments expanded the terminal area operations investigations with consideration of missed approaches and one engine inoperative concerns.

Experiment Facility

Vertical Motion Simulator



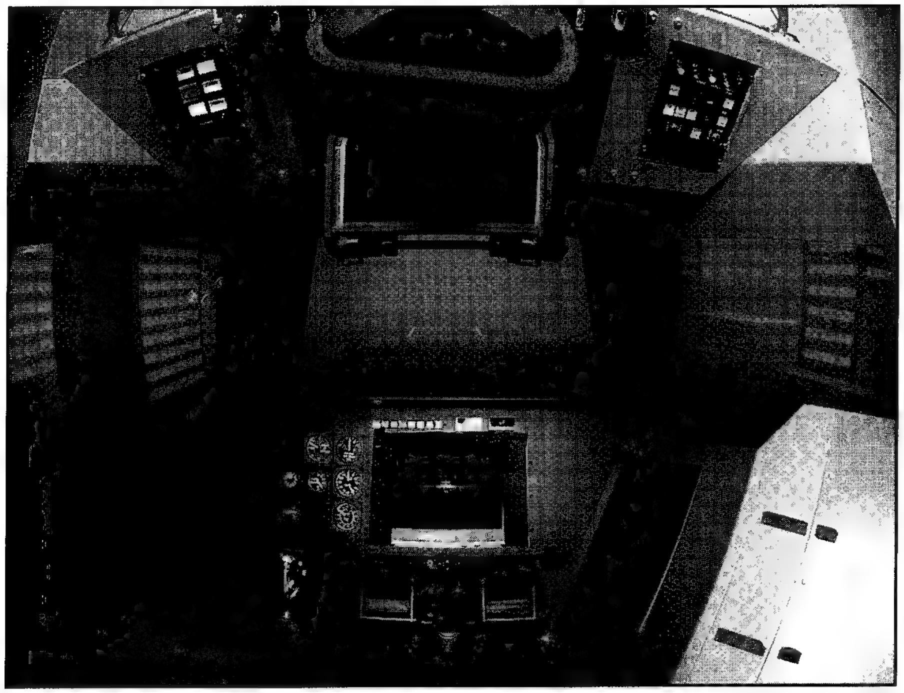
VMS NOMINAL OPERATIONAL MOTION LIMITS			
AXIS	DISPL	VELOCITY	ACCEL
VERTICAL	±30	16	24
LATERAL	±20	8	16
LONGITUDINAL	±4	4	10
ROLL	±18	40	115
PITCH	±18	40	115
YAW	±24	46	115
ALL NUMBERS, UNITS ft, deg, sec			

Aircraft

- **Generic Tiltrotor Simulation Model**
- **40,000 lbs. Transport**
- **Attitude Command SCAS**
- **Torque Command and Limiting System**
- **Automatic Flaps**
- **Nacelle Angle Control Systems**

All of the experiments were conducted in the Vertical Motion Simulator. This facility provides an extremely large motion base platform, ideal for terminal area investigations. In particular, this six degree-of-freedom motion base features a large vertical travel and a choice of one large horizontal axis to provide high bandwidth acceleration cuing. For tiltrotor investigations, the longitudinal axis is emphasized for accelerating and decelerating operations .

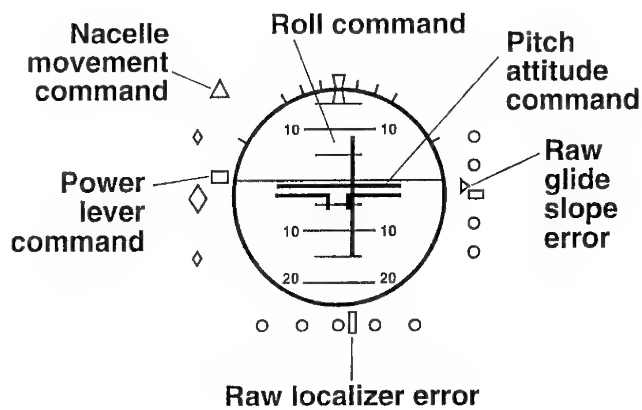
The aircraft was simulated with the Generic Tiltrotor Simulation model, configured as a 40,000 pounds transport. Attitude command control augmentation and a torque command and limiting system were provided. Handling qualities evaluations from the earlier experiments led to the development of automatic flap and nacelle angle control systems that will be discussed later in this presentation.



CTR-2/3 cockpit

The experiments concentrated on handling qualities evaluations by the pilot on controls with only the right cockpit seat provided in the simulator. Shown here is the cockpit configuration used in the early experiments as viewed by the pilot. The visual scene shows the aircraft on short final approach to a vertiport pad located within an "urban canyon." Those are buildings on either side. Cockpit controls include a center stick, pedals, and a thrust control lever with geometry similar to the original V-22 design. Located on the thrust control lever is a thumb-wheel proportional rate control for nacelle movement. A c.r.t. display is located in the center of the panel. Either an electronic analog of conventional round-dial instruments or an advanced primary flight display concept could be shown on this c.r.t.

Flight Director Diagram

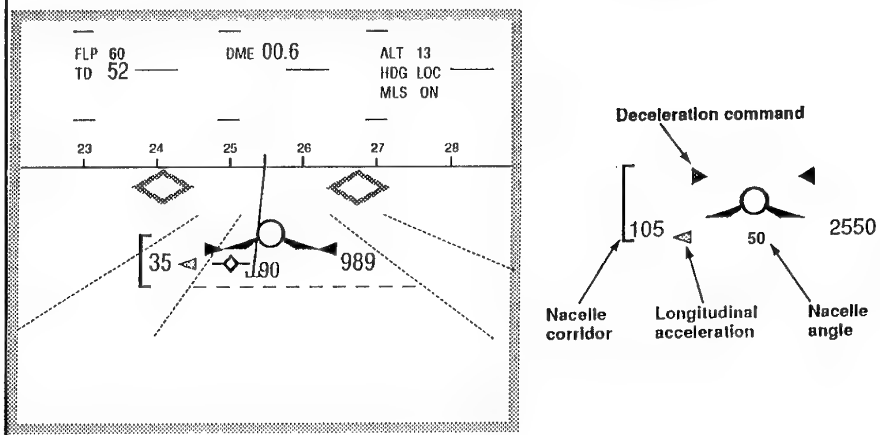


For conventional round-dial instruments, the pilot concentrates on the attitude indicator during instrument operations. As shown here, the raw-data glide slope and localizer error are displayed on the periphery of the attitude indicator. Flight director functions could be displayed with pitch and roll command bars, a power lever cue and a nacelle angle movement prompt, making a four-cue flight director.

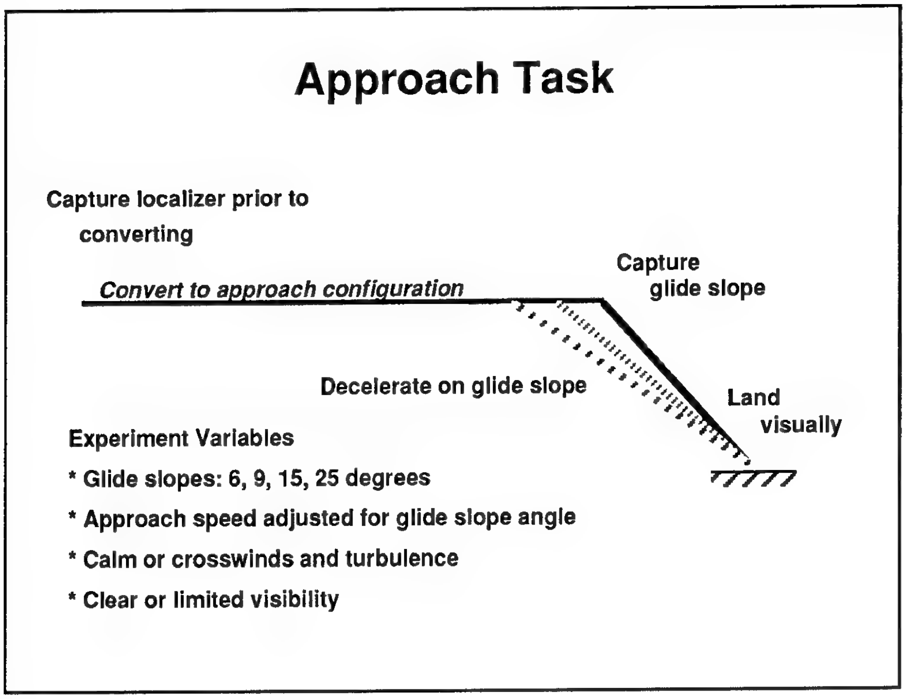
CTR-5 cockpit

The most recent CTR experiment used this cockpit arrangement. The aircraft is shown on approach to a notional vertiport located south of downtown San Francisco. We are at 1000 feet on a nine degree final approach glide slope. Prompted by pilot commentary, the thrust control lever has been changed to a near-vertical movement, similar to the XV-15 control. On top of the thrust control lever head are several switches including a central rocker switch used for a semi-automated nacelle angle control that will be described more later. The panel now includes two c.r.t. displays, inspired by modern fixed wing transport "glass cockpit" layouts. The central attitude indicator on the primary flight display could portray flight director command bars or flight path vector guidance and control symbology under development at Ames.

Flight Path Vector Display



The flight path vector display concept portrays the instantaneous flight path--vertical and horizontal velocity vectors. The pilot controls the aircraft in such a fashion as to overlay the aircraft flight path vector symbol over a leader aircraft symbol. The leader symbol is driven along a "perfect" flight path at a position three seconds ahead of the own-ship. Both the the flight path vector and flight director displays were described in a 1993 AHS paper.



The principal evaluation task for the experiments involved fundamental building blocks of terminal operations: a localizer capture, a level flight conversion from airplane to helicopter mode plus a deceleration to the final approach configuration, glide slope capture and tracking to a landing decision point, and a vertical landing relying on visual references. Glide slopes investigated ranged from 6 to 25 degrees, with the approach speed adjusted for the glide slope angle. Task meteorological conditions included clear-calm and degraded wind and visual conditions.

Steep Approach Operations

Approach Rule of Thumb:

"Descend at no more than 1000 fpm below 1000 feet above ground level."

Glide slope degrees	Airspeed knots	Nacelle Angle degrees
6	80	80
9	55	80
15	35	90
25	20	90

Using an approach operations planning rule of thumb requiring a descent rate lower than 1000 feet per minute on final approach, it becomes a geometric exercise to calculate nominal approach airspeeds. For steeper glide slopes--speculated as necessary for noise minimization and obstacle clearance--very low approach airspeeds are required. Approach nacelle angles were selected to provide nearly deck-level operation. A tiltrotor aircraft has independent control of body attitude at low airspeeds through use of the nacelle angle control.

Task Standards

Maintain flight within:

	Desired	Adequate
<u>Level flight</u>		
Heading	**5 deg**	**10 deg**
Altitude	**50 feet**	**100 feet**
Airspeed	**5 knots**	**10 knots**
<u>Glide slope tracking</u>		
Localizer	**1/2 to 1 dot**	**1 to 2 dots**
Elevation	**1/2 to 1 dot**	**1 to 2 dots**
Airspeed	**5 knots**	**10 knots**

1 dot = 1.25 deg. elevation error or 2.5 deg. azimuth error

Task performance standards must be defined for proper use of the Cooper-Harper Handling Qualities Evaluation System. Adequate performance was based on the FAA's Airline Transport Pilot test standards. Desired performance was set at just half of the adequate. Particularly important for tiltrotor terminal operations are altitude control during a level-flight conversion and glide slope tracking on approach.

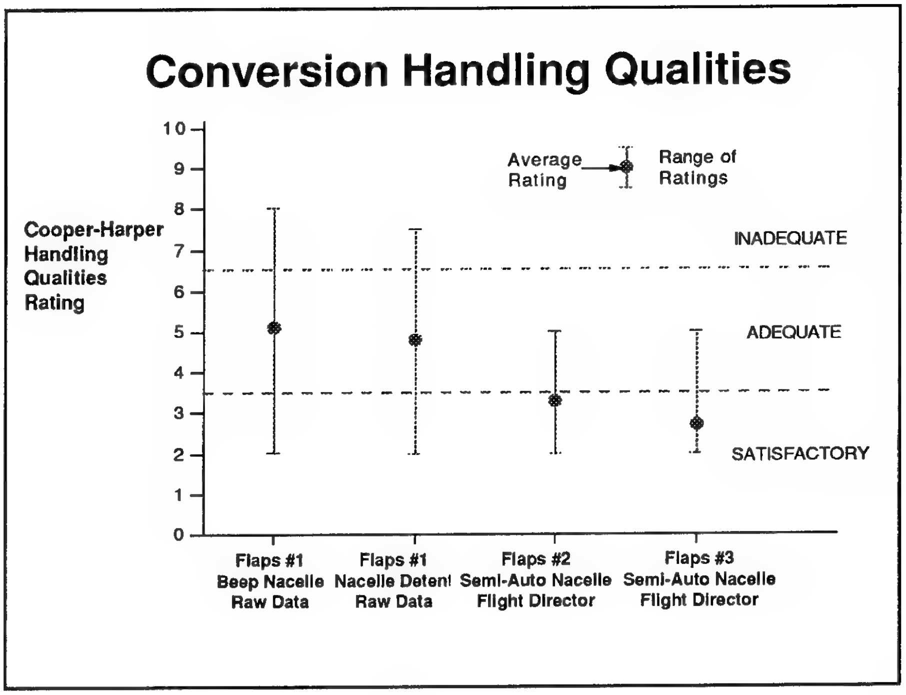
Conversion Systems

- Nacelle angle control
  - manual beep
  - detents
  - semi-automated
- Automated Flaps
  - preliminary military schedules
  - NASA developed schedule

Pilot comments led to the development of cockpit controls to aid the flight mode conversion. For nacelle angle control, the earliest experiments used the “manual beep” control where the pilot had to keep his thumb on the nacelle control movement switch to continuously move the nacelles. This is the system used in the XV-15 and the V-22. Pilot comments suggested the use of a nacelle angle detent system with preselected stops. The pilot could hold down the nacelle movement switch, concentrating on other flight tasks, knowing the the nacelles would stop at the preselected angle. Pilot comments suggested further development, resulting in our current pilot-initiated semi-automated nacelle movement system. The pilot depresses a switch once to move nacelles between the airplane mode at zero degrees and tilt mode at 60 degrees at a slow movement rate. A second switch depression moves nacelles aft to 80 degrees. A third depression moves the nacelles aft to the hover stop, typically between 85 and 90 degrees. The operation is similar to flap selections in a fixed wing transport.

As with the V-22, our CTR transport has automated flaps. Beginning with simple flap schedules used for the original military program, we eventually developed a flap schedule based on both airspeed and nacelle position for the civil transport task. This NASA-developed schedule intends to minimize trim pitch attitude changes.

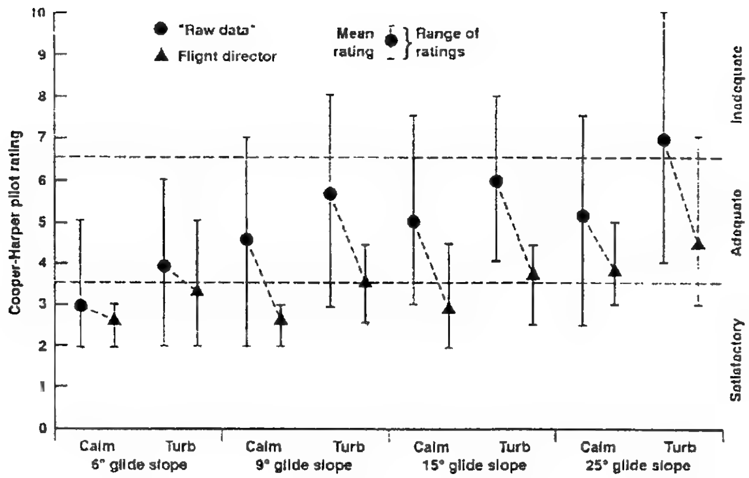
The handling qualities results of these control developments is shown next.



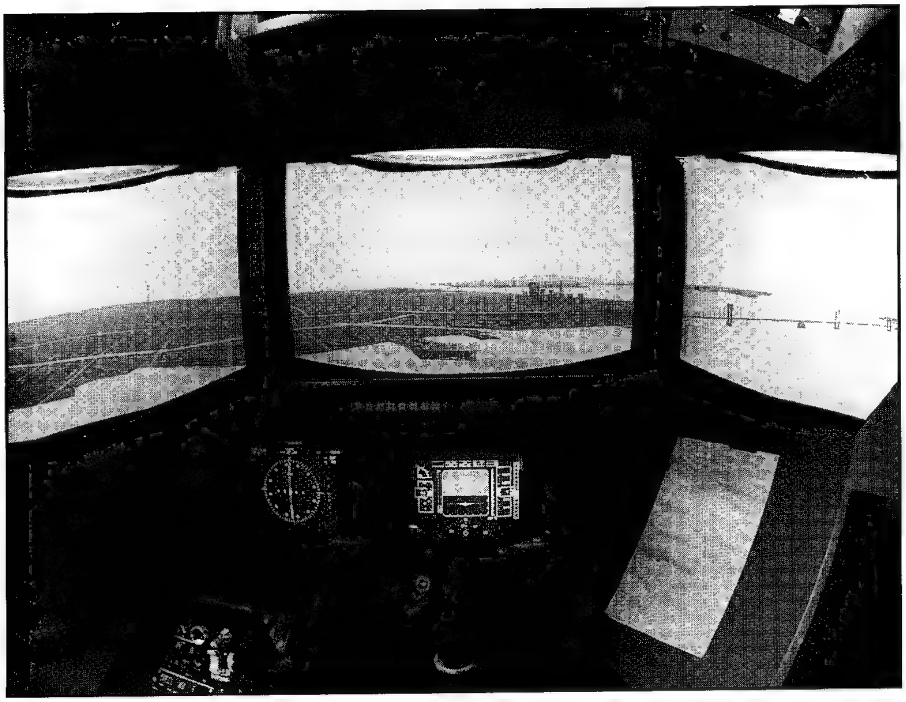
Shown here are Cooper-Harper Handling Qualities ratings for four arrangements of cockpit controls and displays. Beginning with the simple systems of manual beep nacelle control and an abrupt flap schedule, only adequate handling qualities were rated on average with a wide dispersion of ratings depending on pilot tiltrotor experience and weather conditions. The addition of the nacelle detent system provided negligible improvement in quantitative ratings, but associated pilot comments indicated the potential for further improvement. Provision of the semi-automated nacelle control system, a gentler flap schedule and a flight director improved the handling qualities ratings to marginally satisfactory with a greatly reduced dispersion. Finally, our current system with nacelle movement system refinements and the NASA flap schedule provides solidly satisfactory ratings. The simple system evaluations were provided by 6 to 8 pilots while the more recent systems were evaluated by as many as 14 pilots.

Turning now to glide slope tracking.....

Glide slope tracking handling qualities



Shown here are Cooper-Harper Handling Qualities ratings as a function of glide slope angle, weather condition (calm or crosswinds and turbulence) and primary cockpit display. Using only raw data glide slope error guidance (shown by the dots on the left of each group), pilots rated this task as marginally satisfactory for only the shallowest glide slope tested, 6 degrees. Steeper glide slopes which require slow approach speeds on the "back-side" of the power curve drove the ratings into the adequate range or worse. Provision of appropriate cockpit guidance in the form of a flight director or flight path vector display led to more uniform ratings with marginally satisfactory ratings provided on up to a 15 degree glide slope. With their slower approach speeds, crosswinds became more of a problem on the steeper glide slopes. Beginning at 15 degrees, pilot commentary indicated cockpit field of view had become an issue affecting ratings.



CTR-5 cockpit on approach to SFV

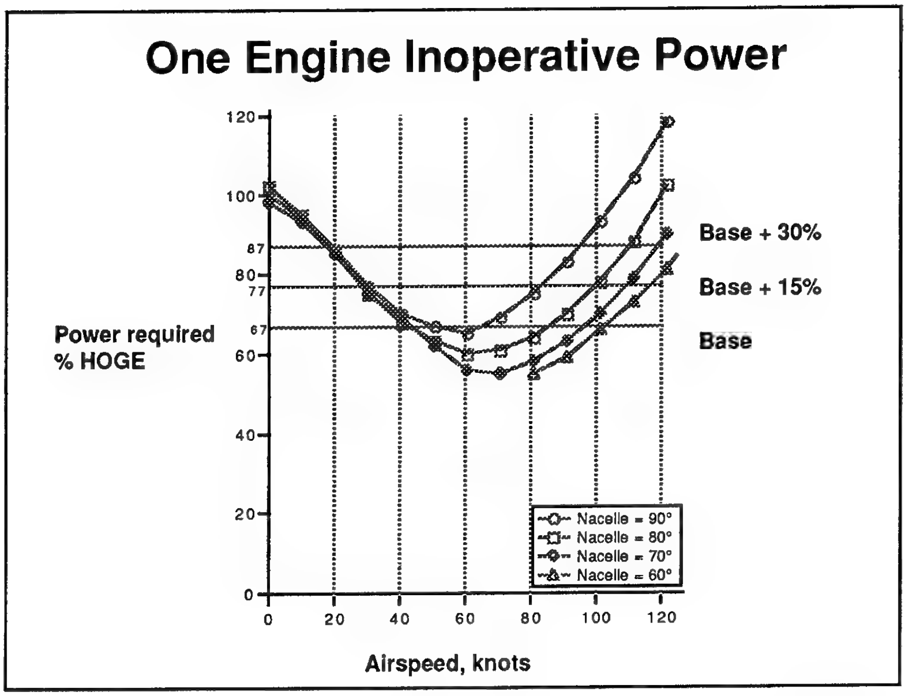
Shown here is the pilot's view from a CTR on a 9 degree final approach. Note that the glide slope aim point at the center of the vertiport is low in the field of view. On a 15 degree glide slope, even with deck level, we are perilously close to the 17 degree look-down angle, typical of many cockpits. Minor variations in flight path caused by atmospheric conditions easily lead to obscuring the aim point under the nose of the aircraft. Certification evaluator-pilots commented negatively on this and degraded their handling qualities ratings as a result.

The field of view issue becomes even more important close to the landing decision point.

CTR-5 LDP @ OAV

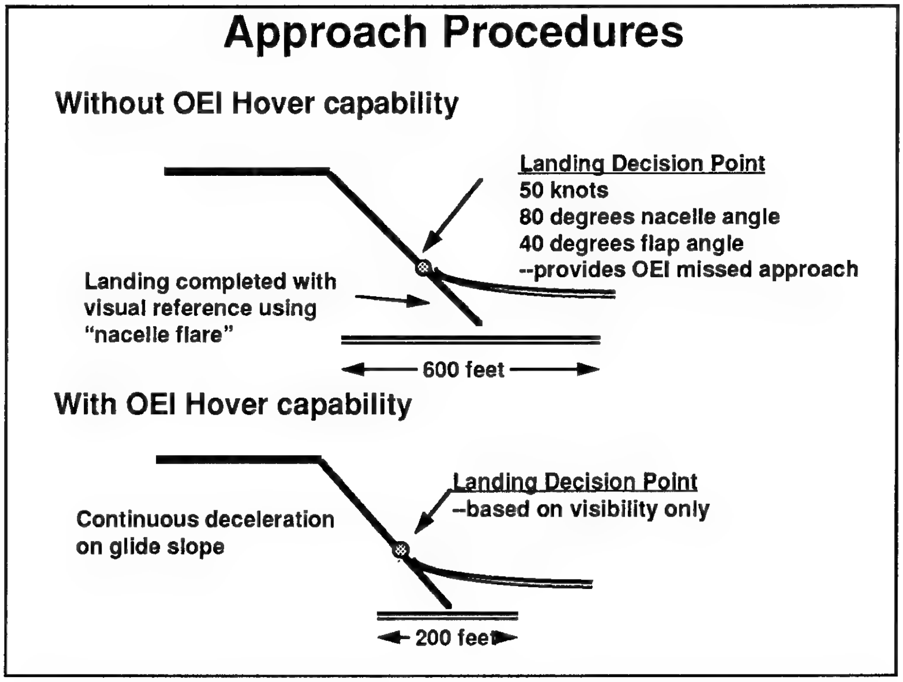
Shown here is the view at a 200 feet high landing decision point for our notional Oakland vertiport. The landing surface is fully in view, but note that any approach lights are obscured below us--precisely at the point in the approach where they are most needed--the transition from instrument to visual flight references. Conversely, "approach" lights on the departure side ARE an aid to landing--both for height control in limited visibility (the horizon obscured) and for lateral line-up. Also shown are a large vertiport symbol, clearly identifiable from the air, and an alternate departure "runway" to better clear obstacles upon departure.

In the low and slow flight condition at the end of the approach, one engine inoperative concerns become essential to operation planning.



Shown here is the power required versus airspeed performance for a variety of nacelle angles from the most recent experiment. The power is normalized at 100% by the power required for hover out of ground effect. A base power was established for each engine by a conservative requirement to provide for OEI service ceiling in the fixed hover configuration. Above this base continuous engine rating, 15% and 30% short-time contingency ratings (30 second ratings) were established for the experiment. 15% contingency ratings are typical of current design practice. A 30% rating is a considerable technological stretch, but provides for hover-in-ground effect up to a 10 feet wheel height for this aircraft.

Using these engine power ratings as experimental variables, a variety of terminal operating strategies were investigated.



For an aircraft without OEI hover capability, an approach procedure was developed to maintain safe OEI missed approach capability until a landing commitment--in visual conditions--could be made. This necessitated keeping 50 knots airspeed and an appropriate aircraft configuration down to 200 feet altitude on a 9 degree approach. Upon landing commitment, the pilot performs a "nacelle flare" (maintaining pitch attitude while moving nacelles aft to to the hover position). This slows the aircraft vertically and horizontally to make a vertical landing. The operation is manageable by the pilot in a repeatable fashion through use of the semi-automated nacelle movement system. This procedure required guiding to the center of at least a 600 feet long vertiport.

Provision of OEI hover capability permitted an alternate approach strategy. The pilot could be guided to a continuous slow deceleration on glide slope to achieve a vertical landing. This strategy received better handling qualities ratings and would support a lower landing decision point, but requires higher power in the event of an engine failure.

Departure operations

- **Non-hover OEI capability**
  - **Vertical departures**
    - » **In H-V avoid region: difficult to control rejected takeoff**
  - **Airspeed over altitude departures**
    - » **Poor repeatable rejected takeoff landing performance**
  - **Rolling takeoff (ESTO)**
    - » **Takeoff decision point (similar to fixed-wing)**
    - » **Low airspeed system required**

- **Hover in ground effect OEI capability**
  - **Add hovering back-up departure from confined spaces**

- **Hover out of ground effect OEI capability**
  - **Pure vertical operations possible**

Turning to departure operations, a variety of strategies were investigated. A vertical technique was quickly discarded since it clearly encroached on a height-velocity avoid region of the flight envelope. Using an "airspeed over altitude" technique--maintaining a low altitude (under 20 feet wheel height) until a safe climb out speed is achieved, pilots still had difficulty judging their touchdown for a rejected takeoff. A better technique with limited OEI performance is an extremely short take off technique. Using airspeed-based take-off decision points (30 knots was recommended), a take-off roll of only a few hundred feet provided for safe, repeatable takeoffs and rejected takeoffs. Indeed, the evaluating certification pilots found they could safely takeoff at a lower airspeed, 20 knots, than the minimum required for out of ground effect level flight. Note that both of these airspeeds are below the speed for reliable use of typical pitot-static airspeed systems. Thus, the need for a good low airspeed system was identified as critical to gaining the most performance (payload) from the aircraft. It should also be noted that the short-time contingency rating was needed for no more than 30 seconds. In all instances, pilots could safely land or accelerate to a safe flight condition within 30 seconds. The tiltrotor's thrust-vectoring is a great help in this operation.

With in-ground-effect hover capability, a hovering back-up technique could be used, permitting operation from confined spaces.

Conclusion

Civil tiltrotor aircraft and infrastructure designs are being developed with extensive use of ground-based simulation.

Traditional Handling Qualities Design Use
- **Controls**
- **Displays and Guidance**

Developing Simulation Roles
- **Procedure Development**
- **Vertiport Design**

In conclusion, the civil tiltrotor simulation program has been used for traditional handling qualities design purposes--control and display design. Developing roles, new to civil aircraft design include procedure development for new aircraft types and development of airport facility designs for these aircraft.

SIMULATION APPLICATIONS IN V-22 AND RAH-66 DESIGN AND DEVELOPMENT

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1. SUMMARY

The Boeing Company Defense & Space Group, Helicopters Division, has increasingly applied constructive and virtual simulation in support of its aircraft developmental programs which include the V-22 Osprey and the RAH-66 Comanche. From their conceptual phases to present, methodologies and mission simulation capabilities have evolved rapidly due to tremendous advances in computing power. By interacting directly with the systems engineering process, simulation has proven to be extremely valuable in optimizing rotorcraft survivability and mission effectiveness. At the same time, simulation has proven to be an effective means of reducing risk and costly flight testing. Recent focus has been on evolving our simulation capabilities for participation in Distributive Interactive Simulation (DIS). These capabilities and their acquired techniques provide potential opportunities to (1) better apply simulation to increase operational effectiveness of future rotorcraft, and (2) facilitate customer involvement in the developmental process.

2. LIST OF SYMBOLS

DIS	distributed interactive simulation
V-22	Osprey tiltrotor aircraft
RAH-66	Comanche armed reconnaissance helicopter
TACAN	tactical navigation device
FLIR	forward looking infrared
Lab	laboratory
AAA	anti-aircraft artillery
SAM	surface to air missile
ATCOM	advanced tactical combat model

3. INTRODUCTION

The demanding environment and missions for which future rotorcraft must be developed and operated are presenting helicopter manufacturers with a truly formidable challenge. In and of itself, rotorcraft flight simulation is a difficult challenge which is made more complex by the application of new technologies. The RAH-66 integrates advanced technologies in the areas of weapons, sensors, signatures, cockpit displays and other mission equipment that require major enhancements to simulation tools previously used. The need to properly represent the influences of terrain, weather and technical sophistication of threat systems are a continuing requirement. The simulation challenges for the V-22 run from the relatively simple to the complicated. For example, proper visual representation of the V-22's nacelles as either vertical or horizontal depending on the flight mode is easy to implement. A more complex challenge is the mathematical calculations required to properly simulate aerodynamics associated with the helicopter-to-airplane transition state.

In addressing these technical challenges, one must not lose sight of fundamental simulation objectives. As an airframe manufacturer and system integrator, organic simulation capabilities must be oriented toward influencing, in a positive way, the development process. This process includes design, systems integration, testing, fielding and training. For most major military development programs, simulation is also used to (1) support the decision process at major milestones, and (2) to help convince political leaders on the importance of a particular development program. To limit the scope of this paper, we will focus on the application of simulation as it pertains to design, systems integration and test support to the RAH-66 and V-22 programs.

Simulation within the U.S. Department of Defense normally has three major categories: constructive, virtual and live (see Figure 1). Constructive simulation includes wargames and math models used as analytical tools to predict system or subsystem performance. Performance includes mission effectiveness, detectability and survivability. Virtual simulation is a virtual reality environment for human interaction. Flight simulators fall into this category. Live simulation is exactly what the word implies. It includes evaluation of hardware on instrumented ranges and larger exercises such as REFORGER (REdeployment of FORces to GERmany).

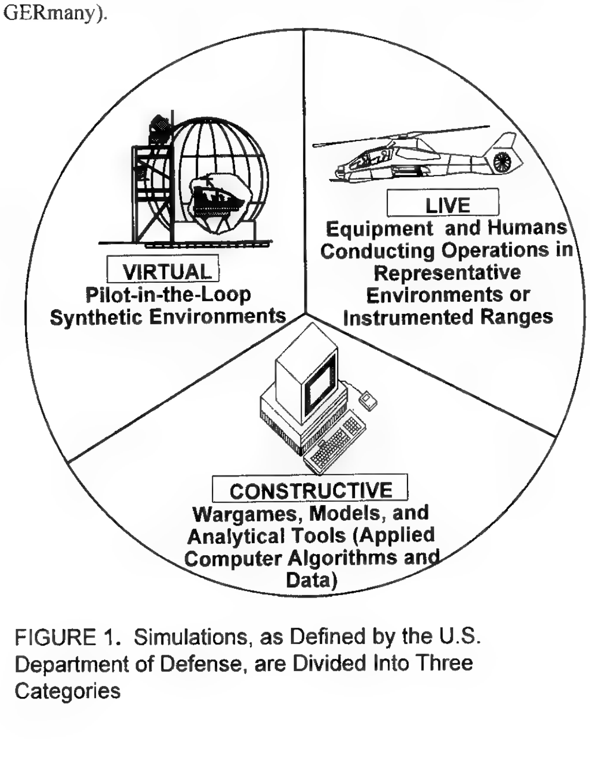


FIGURE 1. Simulations, as Defined by the U.S. Department of Defense, are Divided Into Three Categories

Paper presented at the AGARD FVP Symposium on "Flight Simulation — Where are the Challenges?", held in Braunschweig, Germany, from 22-25 May 1995, and published in CP-577.

4. DESCRIPTION OF RAH-66 AND V-22

The RAH-66 Comanche is the U.S. Army's only new helicopter development program. It is presently in the demonstration/validation phase. The RAH-66 Comanche is a twin-turbine, two-seat (tandem) helicopter that is designed to perform armed reconnaissance for cavalry units and attack missions for the light divisions. For the heavy divisions, Comanche will serve as the aeroscout for the AH-64 Apache. The Marine Corps will use the aircraft to satisfy their medium lift requirements. Because of some unique requirements for special operations, a variant of the V-22 is under development for the Special Operations Command. This variant is designated as "CV-22." Significant systems and key design features of the Osprey include hover flight (helicopter mode), forward cruise flight at 275 knots (airplane mode), an advanced digital cockpit, composite wing and fuselage construction, and

- **Centerpiece of U.S. Army's Aviation Restructure Initiative**
- **High Survivability**
- **Improved Operational Effectiveness**
- **High Reliability**

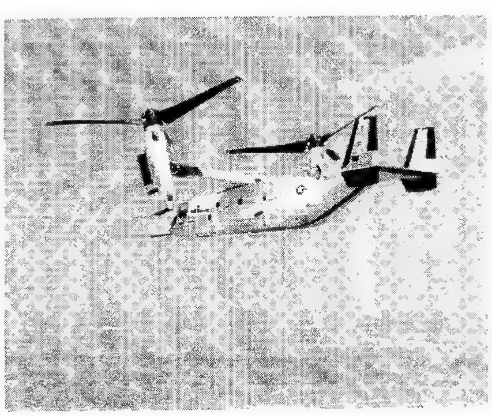
FIGURE 2. The RAH-66 Comanche Program Presents Several Opportunities to Apply Simulation to Meet its Key System Design Requirements

Significant systems and key design features of the Comanche include low signatures (radar, visual, infrared, acoustic); improved target acquisition sensors; increased maneuverability, agility and speed; increased survivability; significantly reduced operation and support costs; and reduced supportability requirements that includes a simple remove-and-replace maintenance concept (see Figure 2). The Comanche will replace U.S. Army AH-1, OH-6 and OH-58 attack and observation helicopters. First flight is scheduled for late 1995. Team Comanche is led by Boeing Defense & Space Group's Helicopters Division and Sikorsky Aircraft Corporation, United Technologies.

The V-22 Osprey is a twin-turbine, vertical-lift, tiltrotor transport. Originally conceived as a joint program for the U.S. Marine Corps, Navy, Air Force, and Army with high dual use potential as a civil transport. Initial production is now targeted for the Marine Corps and U.S Special Operations Command. a cabin that accommodates 24 seats (see Figure 3). The Osprey is being developed under the auspices of the U.S. Naval Air Systems Command by a team of Boeing Defense & Space Group, Helicopters Division and Bell Helicopter Textron.

5. VIRTUAL SIMULATION

Virtual simulation allows pilot interaction with emulated or actual flight controls and displays. Historically, flight simulation has lead the way in successful application of virtual simulation. Flight simulators have been used extensively for pilot training, and they have been used to develop and optimize cockpits for efficient human interaction. Since these applications are well known and understood by the aviation community, this paper will focus on a relatively new application of flight simulation. This application deals with the demonstration, validation and test phases of the development process.



- **Satisfies U.S. Marine Corps' Medium Lift Requirement**
- **Increased Survivability**
- **Improved Operational Effectiveness**
- **Highly Versatile Tiltrotor**

FIGURE 3. The V-22 Osprey Program Introduces Several Unique Simulation Challenges

The V-22 program implements a concept for digitally linking a flight simulator to the laboratories that perform "bench testing" of hardware and software. Mission equipment hardware, flight displays, flight controls, mission computers, avionics, and data busses provided by various subcontractors are mounted in the simulator or connected to the digital network such that they are stimulated by the flight simulator as it performs simulated missions. A fiber optic reflective memory network called SCRAMnet (Shared Common Random Access Memory network) is used to connect the various functions being evaluated. This type of network allows different types of computers to operate on the same network. Of course basic functionality of a piece of hardware is checked prior to testing it as part of the aircraft system.

The real benefit comes from evaluating functionality of these sub-systems as they are being controlled by software that resides in the mission computer and software interfaces between the mission computer and a particular subsystem. This allows nonconfigured software or software patches to be tested in a realistic environment. Such tests (using non-certified software) would not be acceptable for actual flight testing. Another benefit is the speed at which integration concepts can be quickly evaluated. Moreover, feedback to the designers and programmers can also include pilot qualitative evaluations. A massive amount of software is required by the V-22 and RAH-66, so this concept provides a safe means of evaluating system functionality prior to actual flight.

V-22 benefits derived from this concept will be applied to the RAH-66 program. The V-22 program has incorporated a "triple lab tie-in" approach to its integration efforts. The triple lab tie-in digitally links three laboratories (the flight control laboratory, flight simulation laboratory, and mission computer/avionics software laboratory) together. In this way, the V-22 can be virtually "flown" within a laboratory environment. Figure 4 illustrates the triple lab tie-in concept used for the V-22 program. The RAH-66 program plans to use the same concept with the possibility of expanding it for additional laboratories, thereby accommodating target acquisition sensors and weapons systems.

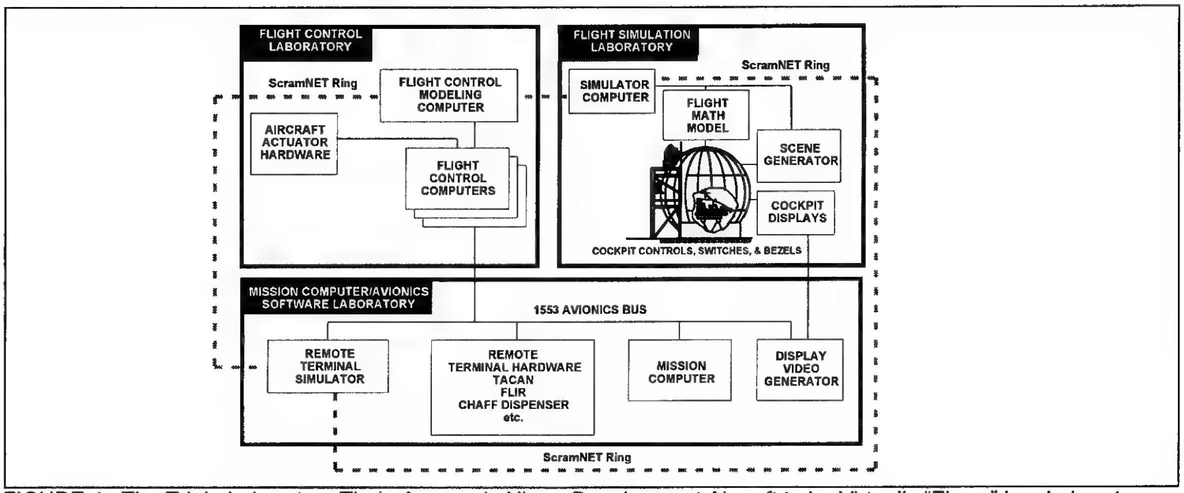


FIGURE 4. The Triple Laboratory Tie-in Approach Allows Development Aircraft to be Virtually “Flown” in a Laboratory Environment

Multiple lab tie-in evaluations have been used for cockpit management system development relative to a dynamic flight scenario environment. Figure 5 illustrates the flow of a typical evaluation.

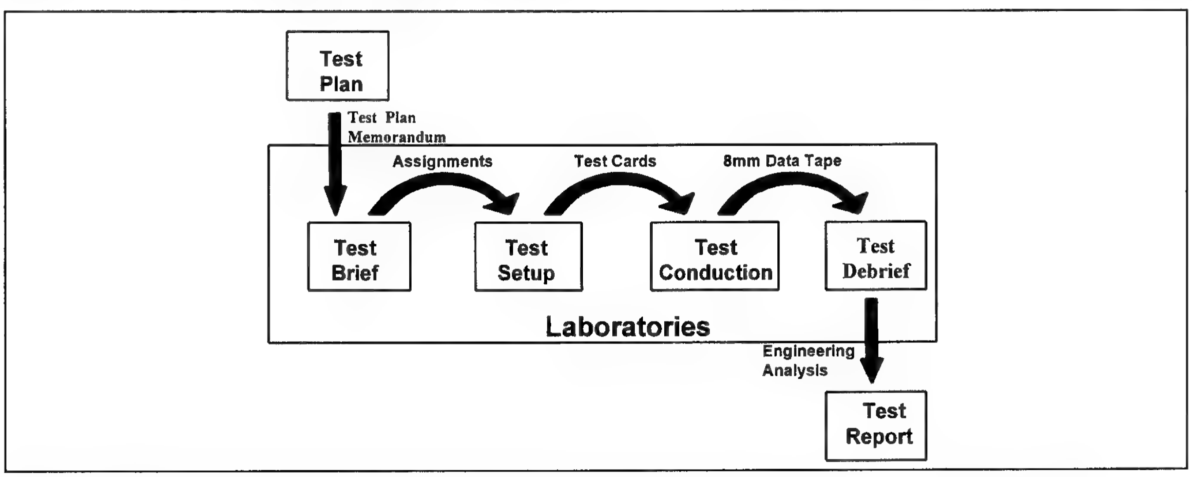


FIGURE 5. A Typical V-22 Triple Laboratory Tie-in Evaluation Mimics the Procedure for a Flight Test Profile

The multiple lab tie-in reduces risk and, through reductions in required flight test hours, there is potential for substantial cost saving. Based on rough estimates from the V-22 program, 43 hours of flight-test reduction would completely pay for the costs associated with the triple lab tie-in (flight testing is approximately 50 times more expensive that simulation). Multiple lab tie-in is also a versatile tool for troubleshooting flight anomalies once flight testing begins.

6. CONSTRUCTIVE SIMULATION

Both V-22 and RAH-66 programs have made rather extensive use of constructive simulation. Because these developmental aircraft have different capabilities and missions, the methodologies and models used differ somewhat. However, due to contractor teaming arrangements and the need to limit the scope of this paper, only the RAH-66 constructive simulation activities will be presented.

program underwent a very thorough Verification, Validation and Accreditation (VV&A) process which was performed by U. S. Army agencies. The greatest discriminator and challenge for selecting, developing and validating the models was in their ability to simulate the effects of terrain on detection, lock-on range and end-game engagements.

The primary application of these models has been to support trade studies and parametric or sensitivity evaluations of alternative design/integration concepts. Other uses include evaluation of candidate technologies for application to the helicopter, periodic mission effectiveness/survivability assessments to measure change as the program progresses and to develop, relative to the current fleet of Army helicopters, comparative data for use in convincing Government officials on the merits of the program. Of course the latter is of little significance to the design process. However, it is an important aspect of a development program during defense cut-backks.

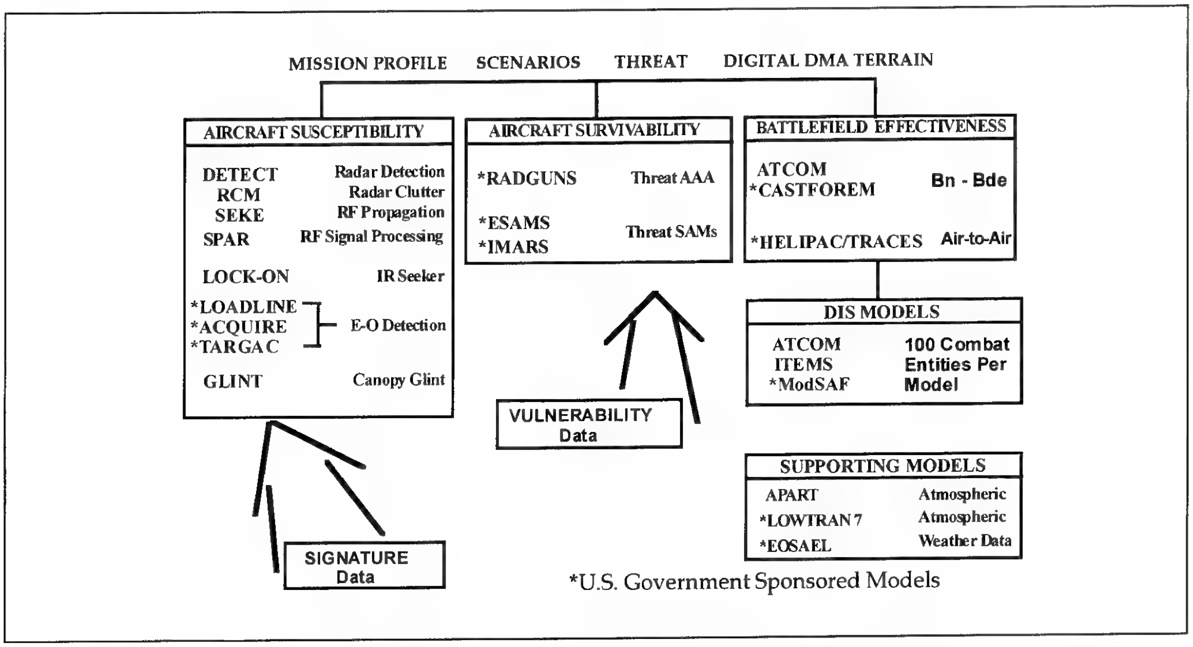


FIGURE 6. A Family of Constructive Simulation Models Are Being Used on the RAH-66 Program to Support Trade Studies and Sensitivity Analyses

Past use of constructive simulation to support design and development of aircraft programs has been predominantly with one-on-one and one-on-few models. However, during the competitive proposal phase of the RAH-66 program, the value of simulating team tactics, techniques and procedures and the synergism of combined arms operations for mission effectiveness and survivability became very apparent. This prompted our use of battlefield simulation models to augment the more traditional survivability models.

Figure 6 depicts the family of constructive simulation models being used on the RAH-66 program and their purpose. Note that many of these models were developed by U.S Government agencies. The other models were developed or purchased to accommodate specific program needs. The models used on the

A general methodology presented by Figure 7 provides a top-down flow of major constructive simulation activities. A player-interactive battlefield simulation model was used, with help from experienced Army pilots, to evaluate several Army scenarios. These simulations served to develop the flight paths, observation positions, and firing positions used by the helicopters relative to the position of threat systems defined in the Army scenarios. Using this data, the detectability and survivability models were run to provide a more detailed evaluation of detection or engagement outcomes. The player-interactive battlefield simulations also served to provide force movements and other data necessary to run the Army's CASTFOREM (Combined Arms and Support Task Force Evaluation Model) simulation which is not player-interactive.

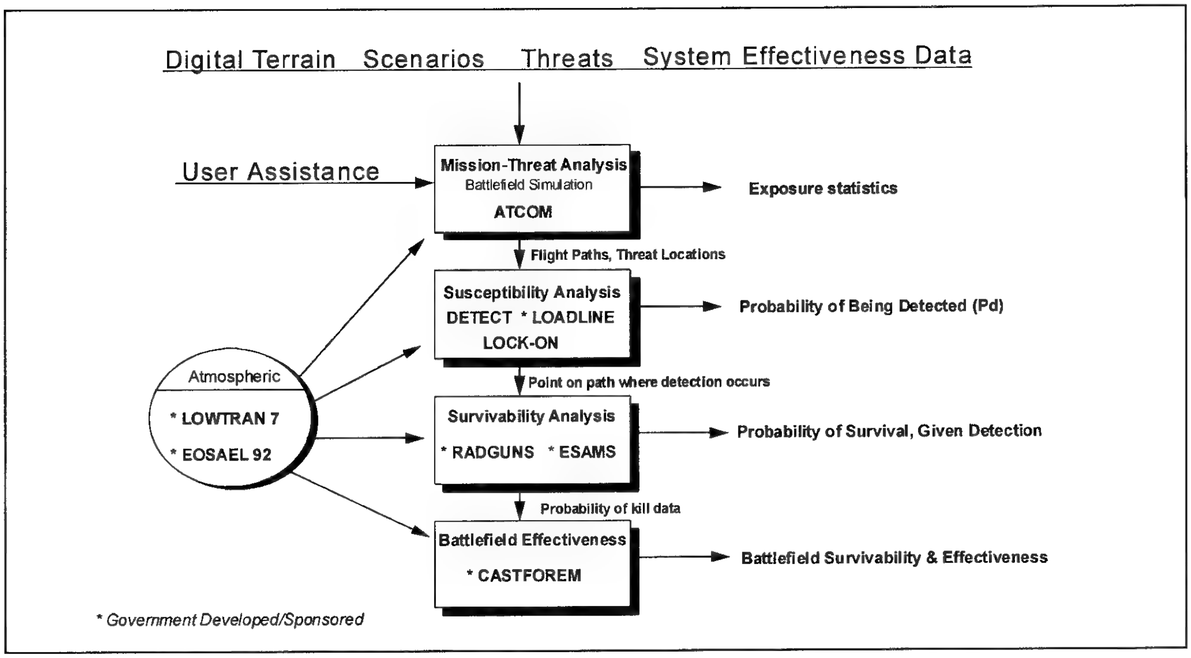


FIGURE 7. Methodology Depicting Flow of Major Constructive Simulation Activities

The RAH-66 program is using a Computer-Aided Design (CAD) tool called CATIA (Computer-Aided, Three-dimensional Interactive Application) that is having a positive impact on both constructive and virtual simulation activities. On the constructive side, this design tool provides, in digital form, the data necessary to define the physical characteristics of the aircraft for visual, infrared and radar signature predictions. However, the process of using this information is not a simple as it may seem. Information from the computer-aided design tools must be processed into a form useable by other models. The other models have their own unique input format, so numerous conversion programs must be developed to make use of data developed by this computer-aided design tool.

7. VISION FOR THE FUTURE

A natural progression of virtual and constructive simulation is to interface the two capabilities. For constructive simulation, this would allow human factors (pilot-in-the-loop) issues to be analyzed and quantified when desired. In other words, variations in cockpit design could be evaluated and quantified in terms of their potential contributions for mission effectiveness and survivability. For virtual simulation, comprehensive battlefield scenarios could be exercised to provide a more realistic simulation environment. Also, more complex interactions between the simulator and other battlefield entities or units could be simulated and evaluated. Presently, there are at least three ways to interface constructive and virtual simulation. They are shared memory, reflective memory and common protocol networks.

Although interfacing virtual and constructive simulation may appear costly, there are potential cost savings. Virtual-Constructive simulations performed with the flight simulator fully manned could be recorded for multiple unmanned reruns with a constructive model. This record-playback capability is useful for parametric and sensitivity analyses which can be executed much quicker without the manned simulator. This is most cost-effective when several small changes or variations to a system or subsystem need to be evaluated.

Most constructive simulation models do not run in a real-time mode which is necessary for virtual simulation. To meet the real-time requirement imposed by virtual simulation, faster computers and multiple processors may be required for constructive models.

A relatively new concept being exploited within the U.S. Defense Department is Distributed Interactive Simulation (DIS). This concept allows dissimilar models distributed over a large geographical area to interact with each other to form a common simulation. It includes connection of live, constructive, virtual and training simulation under a common, synthetic environment, (see figure 8). These simulations communicate over local and wide area networks. Key elements of this concept are:

- No central computer for scheduling or conflict resolution.
- Each node is responsible for maintaining the state of one or more simulation entities.
- Common protocols for communicating entity status/activity.
- Receiving nodes determine what is perceived.
- Only entity state changes are communicated by each node.
- Each node uses dead reckoning to limit communications.

Considerable progress has been made with the DIS concept. The U.S. Department of Defense is exploiting it for three major domains: Research, Development, and Acquisition (RD&A), which includes testing; Military Operations, which includes planning and rehearsals; and Training, which includes integrating live exercises with simulated activities. The DIS

concept has already influenced RAH-66 Comanche program activities, and we are preparing to use it to support V-22 Osprey program activities.

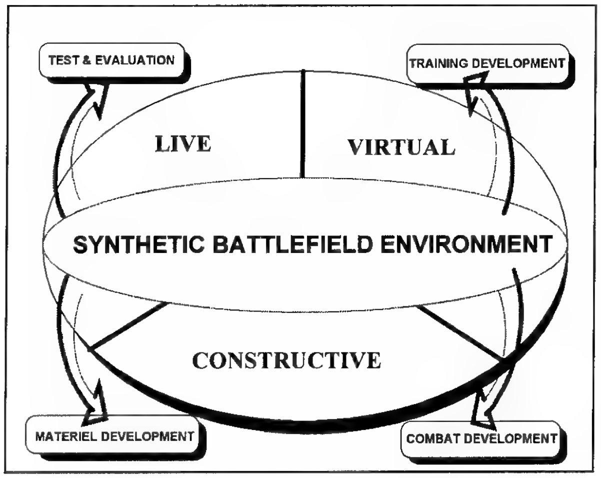


FIGURE 8. Distributed Interactive Simulation Allows Dissimilar Models Distributed Over a Large Geographical Area to Interact with Each Other

Because of the computing power becoming available and rapidly improving quality of simulation, a new concept called "virtual prototyping" is emerging. The U.S. Department of Defense defines the process as:

> "The process of using a virtual prototype, in lieu of a physical prototype, for test and evaluation of specific characteristics of a candidate design."

A virtual prototype is a computer-based, digital representation of a system or subsystem. This concept involves utilization of a collection of simulation tools to guide product design from concept formulation to prototype with emphasis on integration and optimization rather than hardware. It is envisioned that the simulation tools used will bring warfighters, scientists, engineers, testers and manufacturers together to develop and evaluate, both qualitatively and quantitatively, concepts in simulated environments. This would be accomplished by a confederation of computers connected by local and wide area networks. Once a system is optimized and it enters production, the associated simulation tools would also be used for training, doctrine and other purposes.

8. CONCLUSION

Simulation is playing a significant role in the development phases of the RAH-66 and V-22 programs. We, in concert with our team members, are applying both virtual and constructive simulation to optimize the combat effectiveness and survivability of the aircraft. Concurrently, we are recognizing opportunities for better application of simulation, and we are rapidly improving our capabilities in this area. As computer processing speeds increase and networking capabilities improve, simulation will play an even greater role in development of rotorcraft. With future application of virtual prototyping, the necessary synergism between design, manufacturing simulation, and testing will provide new challenges with many potential benefits. Time reduction, efficiency, manpower reduction and risk reduction/abatement are some of the more obvious benefits to the contractor. To the military customer, it will be a better product at a more affordable price.

Piloted Simulation in Rotorcraft Design & Development
EUROCOPTER Experience and Future Trends

La simulation pilotée pour la conception et le développement des appareils à voilure tournantes

L'expérience d'EUROCOPTER et les tendances pour le futur

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SUMMARY

Piloted simulation has largely been used in EUROCOPTER's developments for the last 10 years. For the TIGER attack helicopter, piloted simulation was extensively used from the very beginning of the development to the prototypes' flights. Today, the development of the NH–90 helicopter requires a lot of experimentations on the SPHERE simulator. Piloted simulation is also used for research related to handling qualities, such as the ACT European program, or to Man–Machine–Interfaces (MMIs). The implementation of demonstrators, such as the FBW DAUPHIN, as well as the study of the EUROFAR Tilt–Rotor have also largely involved piloted simulations. A significant experience in testing procedures has been acquired. Environmental and human factors appear to be of the greatest importance. In the future, evolutions are planned to further enhance the representativity of SPHERE simulator. The emergence of new design standards, such as ADS–33C, leads to envisage new applications of piloted simulation.

RESUME

Depuis 10 ans, la simulation pilotée est largement utilisée dans les développements d'EUROCOPTER. Pour l'hélicoptère d'attaque TIGRE, la simulation pilotée fut employée de façon intensive du début du développement jusqu'aux vols des prototypes. Actuellement, le développement de l'hélicoptère NH–90 nécessite de nombreuses expérimentations sur le simulateur SPHERE. La simulation pilotée est également utilisée pour des recherches relatives aux qualités de vol, tel que le programme Européen ACT, ou aux interfaces homme–machine. La mise au point de démonstrateurs, tel que le DAUPHIN CDVE, ainsi que l'étude du convertible EUROFAR ont aussi largement fait appel à la simulation pilotée. Une expérience significative en matière de procédures d'essais a été acquise. L'environnement et les facteurs humains apparaissent être de la plus grande importance. Dans le futur, des évolutions sont prévues pour améliorer encore la représentativité du simulateur SPHERE. L'émergence de nouvelles normes de conception, telles que l'ADS–33C, permet d'envisager de nouvelles applications de la simulation pilotée.

1.ABREVIATIONS

ACT	Active Control Technology
ADS	Aircraft Design Standard
AFS	Advanced Flight Simulator
CDVE	Commandes De Vol Electriques
CELAR	Centre d'ELectronique de l'ARmement
CEV	Centre d'Essais en Vol
CPU	Central Processor Unit
DRA	Defence Research Agency
FBW	Fly–by–Wire
FCC	Flight Control Computer
FLIR	Forward Looking Infra–Red
GE	General Electric
GFF	Government Furnished Facility
HAC	Hélicoptère Anti–Char
HAP	Hélicoptère Appui–Protection
HMS/D	Helmet Mounted Sight/Display
IFR	Instrument Flight Rules
LLLTV	Low Light Level TV
MFD	Multi Function Display
MMI	Man–Machine–Interface
MTE	Mission Task Element
NFH	NATO Frigate Helicopter
NLR	Nationaal Lucht–en–Ruimtevaartlaboratorium
NOE	Nap–Of–the–Earth
PAH	Panzer Abwehr Hubschrauber
PIO	Pilot Induced Oscillations
PFCS	Primary Flight Control System
RFI	Radio Frequency Indicator
RISC	Reduced Instruction Set Computer
SIMCO	SIMulation COckpit
TTH	Tactical Transport Helicopter
UCE	Usable Cue Environment
VMS	Vertical Motion Simulator

Paper presented at the AGARD FVP Symposium on "Flight Simulation — Where are the Challenges?", held in Braunschweig, Germany, from 22-25 May 1995, and published in CP-577.

2. INTRODUCTION

Bien qu'utilisée depuis longtemps dans le domaine des avions, ce n'est qu'au début des années 80 que la simulation pilotée s'est imposée en tant qu'outil d'aide à la conception et au développement des appareils à voilures tournantes. Cet avènement a résulté de la conjoncture de plusieurs facteurs déterminants. D'une part, l'accroissement considérable de la puissance des calculateurs numériques a rendu possible la simulation en temps réel avec des modèles rotor génériques non−linéaires permettant obtenir une bonne représentativité dans l'ensemble du domaine de vol. Dans le même temps, les nouveaux programmes militaires se sont orientés vers le développement de machines très sophistiquées conçues en tant que Système d'Armes et pour lesquelles il devenait indispensable de recourir à la simulation dès le stade de la conception. Enfin, l'émergence des Commandes De Vol Electriques (CDVE) a fait apparaître l'intérêt d'étudier en simulateur, puis en vol, de nouvelles lois de commande visant à réduire au maximum la charge de travail de pilotage.

Dans ce contexte, EUROCOPTER a été amené à concevoir et à mettre en place des moyens de simulation pilotée, matériels et logiciels, qui sont actuellement utilisés avec profit pour le développement des nouvelles machines, telles que le TIGRE et le NH−90.

Cette conférence présente les principaux aspects de l'expérience acquise par EUROCOPTER en matière de simulation pilotée, ainsi que les évolutions envisagées pour le futur.

3. LE PROGRAMME "TIGRE"

L'hélicoptère d'attaque TIGRE est le premier programme d'EUROCOPTER pour lequel la simulation pilotée a été utilisée de façon intensive dès le début du développement. Trois installations d'essais ont été nécessaires pour mener à bien les activités de simulation: SIMCO et les simulateurs du CELAR et du CEV (centres d'essais étatiques) .

Le simulateur SIMCO

Le simulateur SIMCO ("SIMulation COckpit") est installé à Ottobrunn sur le site d'EUROCOPTER DEUTSCHLAND. Il est utilisé pour le développement et la validation des fonctions d'interface homme−machine (MMI) communes aux trois versions du TIGRE: HAP, HAC and PAH−2 (réf. 1).

La cabine de simulation est une réplique fidèle du cockpit en tandem du TIGRE (Fig. 1). L'avionique et les aménagements internes sont très représentatifs et certains équipements sont ceux de l'appareil réel (commandes de vol complètes, HMS/Ds, panneaux de commande, RFIs, et système d'alarmes).

La cabine peut fonctionner de façon autonome pour les essais où la vision du monde extérieur n'est pas indispensable. Lorsque les essais le nécessitent, la cabine est transférée dans le dôme de la DASA, d'un diamètre de 10 m et situé sur le même site, où un générateur d'image GE COMPUSCENE IV à 6 canaux de projection permet d'obtenir une image du paysage avec un champ de vision d'environ 140°(H) x 110°(V) (Fig. 2 & 3).

Le comportement de l'hélicoptère et sa réponse aux commandes sont simulés par le modèle générique de mécanique du vol GENSIM développé par EUROCOPTER−DEUTSCHLAND. Le calcul des efforts aérodynamiques sur la cellule utilise à la fois des données de soufflerie et des formules analytiques. Les efforts rotor sont calculés par un modèle de type élément de pale avec degrés de liberté en battement et en rotation. Les moteurs MTR−390 sont également modélisés, ce qui permet de simuler les variations transitoires de régime rotor lors des manoeuvres. Pour augmenter encore le réalisme de la simulation, on peut adjoindre au modèle de mécanique du vol un modèle de train d'atterrissage, ainsi qu'un modèle simplifié de bruit interne. Un calculateur HARRIS NIGHTHAWK est utilisé pour le calcul et la gestion des modèles de simulation. Le temps de cycle varie de 30 à 40 millisecondes, suivant le degré de complexité choisi pour le modèle de mécanique du vol (réf. 2).

Jusqu'à aujourd'hui, l'activité SIMCO représente plus de 650 heures de simulation effectuées par les pilotes de l'Industrie et des Services Officiels Clients.

Les simulateurs CELAR et CEV

Les simulateurs du CELAR (Centre d'Electronique de l'Armement) et du CEV (Centre d'Essais en Vol) sont tous deux des installations GFF ("Government Furnished Facility") appartenant à l'Etat Français et situées respectivement à Bruz, près de Rennes, et à Istres. Ces installations sont, d'un point de vue matériel, très semblables et sont utilisées essentiellement pour le développement de la version Appui−Protection du TIGRE (HAP) (réf. 3).

Le simulateur du CEV est utilisé pour les études d'interface équipage−système spécifiques à cette version telles que la coordination entre le pilote et le tireur et l'intégration du système d'arme HAP au système de base. De plus, de par sa proximité de Marignane, ce simulateur permet également d'assurer un soutien aux essais en vol des prototypes.

Le simulateur du CELAR est utilisé pour le développement des systèmes de tir canon, missiles Air−Air, et roquettes de l'HAP.

Les simulateurs du CELAR et du CEV sont équipés de 2 cabines représentatives d'un point de vue ergonomique des fonctions MMI à évaluer et en accord avec les évolutions successives de définition. Les cabines "Pilote" et "Tireur" sont séparées et chacune comprend son propre système d'image de synthèse pour la vision du monde extérieur. La cabine du pilote est équipée d'un système hydraulique restituant les efforts de commandes, d'un générateur d'environnement sonore et d'un siège vibrant.

La vision extérieure et les images senseurs sont obtenues par des générateurs d'image SOGITEC GI–10K SOGITEC. Le système de projection à trois canaux dans un dôme d'environ 10 m de diamètre permettent au pilote une vision du monde extérieur sur un champ de 200°(H) x 55°(V). Les images vues par les différents senseurs de tir sont envoyées au tireur dans l'oculaire du viseur et (ou) sur les écrans multi–fonctions (MFDs). La base de données du système de vision a été spécialement développée pour le vol hélicoptère à proximité du sol et des obstacles (vol NOE). L'image d'un autre hélicoptère en vol (escorte ou cible) peut également être présentée.

4. LE PROGRAMME NH–90

Le développement de cet hélicoptère, qui a débuté en 91 et dont le premier vol est prévu fin 95, engendre un volume très important de simulations. D'une part, le développement actuellement en cours des Commandes De Vol Electriques (CDVE) impose une utilisation intensive de la simulation pilotée pour l'étude et la définition des lois de commandes, ainsi que pour la validation avant vol du fonctionnement de ce système. D'autre part, les performances de mission élevées requises pour cet appareil, que ce soit en version terrestre (TTH) ou marine (NFH), conduisent à des études de définition particulièrement poussées des interfaces équipage–système (MMIs) et qui devront être validées par de nombreuses évaluations en simulateur. Le volume des évaluations nécessaires en simulateur est par ailleurs accru du fait de la diversité des missions terrestres et navales, résultant elle même du nombre important d'Armées–Clientes (4 Marines, 3 Armées de Terre). Depuis le début du programme NH–90, plus de 1000 heures, dont environ 1/3 avec des pilotes, ont été effectuées en simulateur pour la définition et le développement du PFCS (Primary Flight Control System). Les simulations pilotées relatives aux MMIs doivent débuter en 96.

Les simulations pilotées du programme NH–90 utilisent essentiellement le moyen d'essais SPHERE implanté sur le site d'EUROCOPTER–FRANCE à Marignane (Fig. 4).

Les simulations PFCS

Ces simulations permettent de développer les lois de commande (ou lois de pilotage) du PFCS de façon à satisfaire les objectifs retenus en matière de qualités de vol. Ces objectifs sont dérivés des critères de l'ADS–33C (réf. 4) en tenant compte de la nature des missions des versions TTH et NFH. La simulation pilotée est utilisée d'une part pour valider en temps réel le fonctionnement des lois de commandes, et d'autre part pour s'assurer que la structure et le réglage de ces lois permettent effectivement d'obtenir une charge de travail de pilotage faible, donc des qualités de vol de Niveau 1, pour chaque élément de mission (MTE).

Le cockpit utilisé est une cabine de pilotage côte–à–côte multi–usages (cockpit expérimental) dont les dimensions, la position des commandes et le champ de vision peuvent être considérés comme représentatifs d'un appareil de type NH–90, bien que pas tout à fait conformes à la définition actuelle de cet hélicoptère.

Seule la place droite est utilisée pour les simulations PFCS. Un système hydraulique de restitution d'efforts MAC FADDEN permet d'obtenir des caractéristiques d'effort et de déplacement des commandes conformes à celles visées pour l'appareil réel. Sur la planche de bord, des écrans graphiques permettent d'afficher les paramètres de vol nécessaires pour le pilotage de base et pour réaliser les éléments de mission. La symbologie utilisée est de type expérimentale et n'est pas complètement représentative de celle prévue pour l'appareil réel.

Le cockpit expérimental est placé sur une base fixe dans le dôme SPHERE de 8 m de diamètre. Un système de projection d'image de synthèse à 3 canaux SOGITEC GI 10K permet d'obtenir une vision du monde extérieur sur un champ de 180°(H) x 80°(V) (Fig. 5 & 6). La base de données principale, de dimensions 14 x 10 Km et hautement détaillée, a été spécialement conçue par SOGITEC pour le vol tactique hélicoptère et comporte de nombreux obstacles naturels et artificiels. Une autre base de données, plus vaste mais moins détaillée, comporte une étendue maritime avec un navire, de type frégate, pouvant être animé de mouvements en relation avec l'état de la mer. Ceci permettra, pour la version navale NFH, d'analyser en simulateur certains aspects relatifs aux manoeuvres d'atterrissage sur pont de navire.

Le comportement de l'hélicoptère et sa réponse aux commandes sont simulés par le modèle générique de mécanique du vol S89 développé par EUROCOPTER–FRANCE. Des essais effectués au NLR (Nationaal Lucht en Ruimtevaartlaboratorium, Netherlands) avec des maquettes de soufflerie motorisées et non–motorisées ont permis de recaler le modèle de calcul des efforts aérodynamiques sur la cellule. Les efforts rotor sont calculés par un modèle de type analytique avec degrés de liberté en battement et en rotation. Une version avec modèle type "élément de pale" est également disponible. Les moteurs ne sont pas pour le moment modélisés, mais un modèle dynamique des moteurs RTM 322 sera intégré à la simulation courant 95.

Le PFCS est simulé par un modèle utilisant la même spécification de code que celle prévue pour les calculateurs FCC réels (Flight Control Computers). Ceci permet de garantir l'identité des lois de commande entre l'appareil simulé et l'appareil réel. Les réponses des servo–commandes et des capteurs sont simulées par des modèles en accord avec les spécifications de ces équipements (bandes passantes, retards) et seront recalés ultérieurement, si nécessaire, en fonction des performances réelles constatées.

L'ensemble des calculs relatifs aux modèles de simulation sont effectués par des CPUs de

technologie RISC implantées sur des cartes VME 32 bits. Le temps de cycle global est de 40 milli−secondes (25 Hz). Le retard de l'image est entièrement compensé par un algorithme d'extrapolation (réf. 5), ce qui réduit au minimum le délai entre une action pilote et la réponse visuelle du modèle.

5. RECHERCHE APPLIQUEE

En parallèle aux activités liées aux développement d'hélicoptères nouveaux, la simulation pilotée est également largement utilisée par EUROCOPTER dans le cadre de programmes de recherche appliquée ou du développement de démonstrateurs technologiques.

Le programme ACT (Active Control Technology), réalisé en coopération entre la France, l'Allemagne et la Grande Bretagne, a pour objectif d'étudier les nouveaux concepts rendus possibles par l'introduction des commandes de vol électriques (ou optiques) telles que les lois de commandes évoluées et les mini−manches (réf. 6). Les simulations pilotées relatives à ce programme ont été effectuées sur différents moyens d'essais mis à disposition par l'Industrie (simulateur SPHERE à Marignane, simulateur DASA d'Ottobrunn) et par les organismes de recherches (simulateur AFS du DRA Bedford).

EUROCOPTER effectue également des recherches en matière d'interface homme−machine. La simulation pilotée est par exemple utilisée pour évaluer l'impact de nouvelles symbologies de planche de bord sur la charge de travail de l'équipage.

La mise au point des lois de pilotage de l'hélicoptère DAUPHIN 6001, appareil démonstrateur de Commandes de Vol Electriques (réf. 7 & 8), a fait largement appel à la simulation pilotée, dans un premier temps sur les installations étatiques (CEV, CELAR) puis sur SPHERE. Le DAUPHIN 6001 est actuellement utilisé dans le cadre du programme ACT pour l'évaluation en vol de nouvelles lois de pilotage.

Des lois de pilotage adaptées à un appareil de type convertible à rotors basculants (Tilt−Rotor) ont également été étudiées en simulateur dans le cadre du programme européen EUROFAR (réf. 9). En attente du lancement de la phase de définition d'un appareil démonstrateur, les simulations pilotées sont actuellement orientées vers l'étude des trajectoires d'approches à forte pente.

6. PROCEDURES D'ESSAIS ET FACTEURS HUMAINS

Lorsque la simulation pilotée est utilisée dans le cadre de programmes étatiques majeurs, tels que le TIGRE ou le NH−90, différents types d'essais doivent être considérés.

En effet, bien que la simulation soit essentiellement un outil d'étude à la disposition des ingénieurs et pilotes de l'Industrie, les Services Officiels clients demandent toujours à être impliqués dans ces activités. Ceci est principalement lié au fait que la simulation pilotée donne des résultats concrets et directement interprétables, permettant aux clients de suivre au plus près et de valider les différentes étapes des développements. EUROCOPTER a donc été amené à définir et à organiser des sessions de simulations spécifiques pour présenter aux clients les choix techniques en matière d'interfaces homme−machine (MMI) et de systèmes de commandes de vol.

Les clients sont en général fortement impliqués dans les processus de définition des interfaces homme−machine. Dans le cadre du programme TIGRE, les pilotes−clients ont participé à de nombreuses sessions de simulation pilotée en vue d'optimiser et de valider la définition des interfaces de pilotage, notamment en ce qui concerne les symbologies de planche de bord. Un processus similaire d'évaluation en simulateur est prévu pour le NH−90 à partir de 96.

En matière de développement de systèmes de commandes de vol, la participation des clients aux simulations pilotées doit être organisée de façon à obtenir des résultats cohérents et non biaisés malgré l'influence défavorable de l'environnement simulateur sur les évaluations de qualités de vol.

Dans ce but, les pilotes représentant les Services Officiels clients sont invités à effectuer, comme pour des essais de recherche, les évaluations sur des manoeuvres types préalablement définies et à quantifier la charge de travail suivant l'échelle de Cooper−Harper (réf. 10). Les notes sont ensuite moyennées afin obtenir une estimation du niveau de qualité de vol pour chacune des manoeuvres.

Le recours aux manoeuvres types est essentiel pour la cohérence des résultats car c'est la seule façon de garantir que les tous pilotes effectuent les mêmes tâches de pilotage. L'expérience passée d'EUROCOPTER a montré que des évaluations libres sans programme précis conduisaient à des résultats très disparates et difficilement exploitables, chaque pilote ayant tendance à se focaliser sur un aspect particulier de la simulation.

De même, l'utilisation de l'échelle de Cooper−Harper oblige les pilotes à rationaliser leurs jugements, évitant ainsi d'introduire trop de subjectivité dans les appréciations. Pour que les résultats soient valides, il est également important que les pilotes se réfèrent au questionnaire de l'échelle avant d'émettre une note. Beaucoup de pilotes ont malheureusement, tendance à vouloir court−circuiter cette étape. Pour éviter de telles erreurs de procédure, une table de Cooper−Harper est systématiquement présentée au pilote dans le cockpit à la fin de chaque manoeuvre−type.

Les effets induits par l'environnement simulateur doivent également être considérés lors de l'analyse des résultats, surtout compte tenu du fait que certains pilotes des Services Officiels clients peuvent n'avoir que peu d'expérience en simulateur, ou bien une expérience limitée aux simulateurs d'entraînement au vol IFR.

Lorsque des difficultés de pilotage sont rencontrées pendant la réalisation d'une manoeuvre, la première tendance des pilotes est souvent de conclure qu'il y a un problème de contrôlabilité du modèle alors que ceci est parfois la conséquence d'un manque d'adaptation à l'environnement de simulation. En particulier, l'expérience a montré que ceci pouvait conduire certains pilotes à se générer artificiellement, par leurs propres actions aux commandes, une charge de travail excessivement élevée même dans des cas de vol où le modèle est réputé très stable et facile à contrôler. L'expérimentateur doit alors trouver les justes arguments pour amener le pilote évaluateur à reconnaître que ses difficultés sont, en partie ou en totalité, dues à un manque d'adaptation au simulateur.

D'un point de vue général, l'expérience a montré que les pilotes ayant l'habitude de voler sur simulateur, même sur une autre installation, réalisent les meilleures performances sur les manoeuvres–types et sont également plus efficaces pour faire la distinction entre les problèmes liés à l'environnement et les véritables défauts de qualités de vol du modèle de simulation. Le fait de posséder ou non une formation de pilote d'essais, et en particulier l'habitude d'utiliser l'échelle de Cooper–Harper, apparaît également déterminante mais sans doute à un degré moindre que l'expérience en simulateur.

7. ENVIRONNEMENT

L'environnement du simulateur doit fournir les sensations nécessaires au pilotage, en complément des informations affichées sur la planche de bord. Son niveau de représentativité doit être adapté à la nature des essais à effectuer, le but étant d'éviter les excès de détails inutiles et couteux.

Base fixe ou base mobile

Un des premiers problèmes auquel a été confronté EUROCOPTER lors du développement du simulateur SPHERE était de déterminer s'il était nécessaire ou non de restituer les accélérations à court terme au moyen d'une base mobile. Dans ce but, une équipe composée d'un ingénieur et d'un pilote a eu pour mission de visiter et d'évaluer différentes installations existantes de simulation hélicoptère, avec et sans base mobile. La conclusion de cette mission a été que, avec les débattements de plate–forme relativement faibles habituellement utilisés, les accélérations restituées par le mouvement sont insuffisantes, ou trop rapidement évanouies, pour améliorer de façon significative la précision de pilotage lors des évolutions à basse vitesse près du sol et qu'il est plus important de privilégier la qualité du système de vision. Les plate–formes à grand débattement, telles que le VMS (NASA) et le AFS (DRA), semblent actuellement être les seules capables de restituer de façon satisfaisante les accélérations mais restent de part leur coût et leur complexité de mise en oeuvre réservés aux grands centres de recherche étatiques. EUROCOPTER s'est donc logiquement orienté vers le choix d'un simulateur à base fixe mais équipé d'un système de vision performant. Ce choix a été également en partie justifié par les bons résultats obtenus avec le simulateur à base fixe de la DASA, notamment lors des simulations SIMCO associées au programme TIGRE.

Visualisation du monde extérieur

La qualité de l'environnement visuel dépend de plusieurs facteurs. L'étendue du champ de vision est déterminante pour la perception des assiettes et des vitesses et ceci d'autant plus que la vitesse d'avancement est faible, ce qui est le cas typique d'un hélicoptère en évolutions autour du stationnaire ou en vol tactique (NOE). Lors du développement du simulateur SPHERE, le champ de vision horizontal a été, comme prévu, étendu d'abord de 60° à 120°, puis de 120° à 180°, chacune des étapes correspondant à l'adjonction d'un canal de projection supplémentaire. Il fut alors intéressant de constater, pour un même modèle d'hélicoptère, l'amélioration de la pilotabilité en stationnaire au fur et à mesure de l'augmentation du champ de vision horizontal. L'amélioration, bien qu'ayant été la plus significative entre 60° et 120°, est aussi apparue nettement perceptible lors du passage de 120° à 180°, ce qui démontre bien l'importance de la vision périphérique pour le vol à basse vitesse.

Les retards induits par le temps de calcul de l'image ont aussi beaucoup d'importance et doivent être autant que possible minimisés. Sur simulateur à base fixe, les retards peuvent pratiquement être compensés en totalité au moyen d'un algorithme extrapolateur tel que celui décrit dans la référence 5. Une telle approche n'est pas toujours possible avec une base mobile où, pour assurer la cohérence entre l'image et le mouvement, le retard image doit rester comparable à celui de la plate–forme (réf. 11).

Le niveau de détail de la base de données a également une influence importante sur les sensations visuelles lors de la réalisation de manoeuvres de précision près du sol. Il est cependant apparu que la nature et la disposition des obstacles représentés étaient bien plus déterminants que la densité totale de détails figurant dans l'image. Ainsi une zone très riche en détails n'est pas obligatoirement celle qui procure les meilleures sensations visuelles pour le pilotage. Cet aspect pourrait être considéré par les concepteurs de bases de données afin de limiter la puissance de calcul nécessaire pour la génération des images.

La base de donnée VOLTAC utilisée dans le simulateur SPHERE a été spécialement conçue pour le vol hélicoptère près du sol (NOE). En complément des détails intégrés au paysage (arbres, ponts, maisons, ...etc.), des obstacles artificiels ont été placés en différents endroits pour servir de repères visuels lors de la réalisation de certaines manoeuvres–types (Fig. 7). L'importance de la disposition des obstacles a été clairement mise en évidence lors d'essais avec le modèle NH–90 dépourvu de tout dispositif de stabilisation (appareil nu), une nette tendance au pompage piloté (PIO) apparaissant dans certains

endroits de la base de données, ou lorsque orienté d'une certaine façon par rapport à un obstacle. D'une manière générale, les défauts d'environnement visuel ont d'autant plus d'influence sur la pilotabilité que le modèle hélicoptère est instable (appareil nu ou avec stabilisation coupée). Ceci est tout à fait en accord avec la philosophie de l'ADS−33C qui établit une corrélation entre le niveau d'environnement visuel (UCE) et le niveau de stabilisation nécessaire pour obtenir des qualités de vol de niveau 1.

Sons et vibrations

La restitution de l'environnement sonore et des vibrations, peut également apporter des sensations utiles au pilote lors de l'exécution de certaines manoeuvres. Ceci a été utilisé avec profit dans le cadre des simulations TIGRE.

Le cockpit du simulateur SIMCO est restitue l'ambiance sonore dans les écouteurs du casque du pilote et les vibrations par l'intermédiaire d'un coussin de siège gonflable. Les sensations ainsi obtenues sont apparues utiles pour évaluer certaines conditions de vol, en particulier les manoeuvres à fort facteur de charge, les manoeuvres de flare, les descentes rapides et les autorotations.

Les cockpit des simulateurs CEV et CELAR sont également équipés d'un tel système, avec en plus la capacité de restituer le bruit produit par le tir des armements.

8. EVOLUTIONS FUTURES

A partir de cette expérience acquise, EUROCOPTER a identifié les évolutions souhaitables en vue d'améliorer les performances et la représentativité de ses moyens de simulation, et en particulier celles du simulateur SPHERE.

Il n'est pour le moment pas envisagé d'évoluer vers un système à base mobile. Les nombreuses expérimentations effectuées sur SPHERE depuis sa mise en service en 92 semblent confirmer que, pour ce qui est des simulations relatives à la conception et aux développement d'appareils nouveaux, une installation à base fixe est suffisante dans la mesure où celle−ci est principalement utilisée par des pilotes d'EUROCOPTER accoutumés à ce moyen d'essais. Seul l'absence d'accélérations verticales apparaît quelque peu pénalisant, en particulier lors des manoeuvres à très basse vitesse près du sol et lors des atterrissages. Pour compenser en partie et au moindre coût ce manque de sensation, il est prévu à partir de 96 d'équiper les cockpits de simulation de sièges à coussins gonflables permettant de restituer à très court terme le facteur de charge vertical (g−seat).

Le système de visualisation actuelle SOGITEC GI−10K à 3 canaux répond également bien au besoin des essais effectués. Le champ de vision actuel (80°x 180°) apparaît tout à fait suffisant pour effectuer toutes les manoeuvres types, y compris celles comportant des phases de translation latérales (sidestep, pirouette). Par le biais d'un accroissement de la puissance de calcul, il serait possible d'améliorer la fluidité de l'image lors des manoeuvres de rotation rapides, notamment en roulis et en lacet, en multipliant par 2 la fréquence de génération d'image (50 Hz au lieu de 25 Hz). Cependant, le bénéfice apporté par une telle modification serait faible comparé à son coût. EUROCOPTER préfère donc attendre la disponibilité des générateurs d'images de nouvelle génération pour faire évoluer le système de vision de SPHERE. Ces nouveaux générateurs d'image devraient permettre, grâce aux textures plus fines, d'améliorer de façon significative la perception des distances par rapport aux obstacles et au sol, cette perception étant actuellement jugée insuffisante par les pilotes.

Des enrichissements de la base de données sont aussi prévus en fonction de l'évolution des besoins des utilisateurs. Actuellement, EUROCOPTER développe un modèle d'animation de mouvement de navire en fonction de l'état de la mer, ceci en vue de permettre des simulations d'appontage de la version marine du NH−90 (NFH).

La représentativité du modèle temps réel de mécanique du vol hélicoptère sera également améliorée dans le futur par l'introduction de modélisations plus complètes des rotors (mouvements de traînée et de torsion des pales) et des interactions aérodynamiques entre les rotors et la cellule.

Dans le cadre du programme NH−90, un cockpit de simulation totalement représentatif de la définition réelle de l'appareil sera prochainement mis en oeuvre sur SPHERE pour réaliser les simulations MMI relatives au système de base et à la version transport tactique (TTH).

En ce qui concerne les procédures d'essais, il est vraisemblable que dans le futur, les aspects MMI et Qualités de Vol tendront de plus en plus à être traités simultanément au cours des développements. Comme le précise l'ADS−33C, la charge de travail de pilotage dépend non seulement de la réponse de l'appareil aux commandes, mais également de la qualité des informations visuelles dont dispose le pilote. Les développements en simulateur de nouvelles lois de commandes optimisées pour le vol en conditions d'environnement visuel dégradé devront donc s'effectuer en parallèle avec ceux des images et symbologies associées aux systèmes d'aide à la vision (FLIR, LLLTV). Par ailleurs, l'expérience a montré que lors des évaluations de lois de commande avec mini−manches, une part significative de la charge de travail de pilotage pouvait être induite par des problèmes ergonomiques. Les développements futurs utilisant des nouveaux concepts de commande devront donc intégrer, dès la phase de conception initiale, les aspects Qualités de Vol et MMI.

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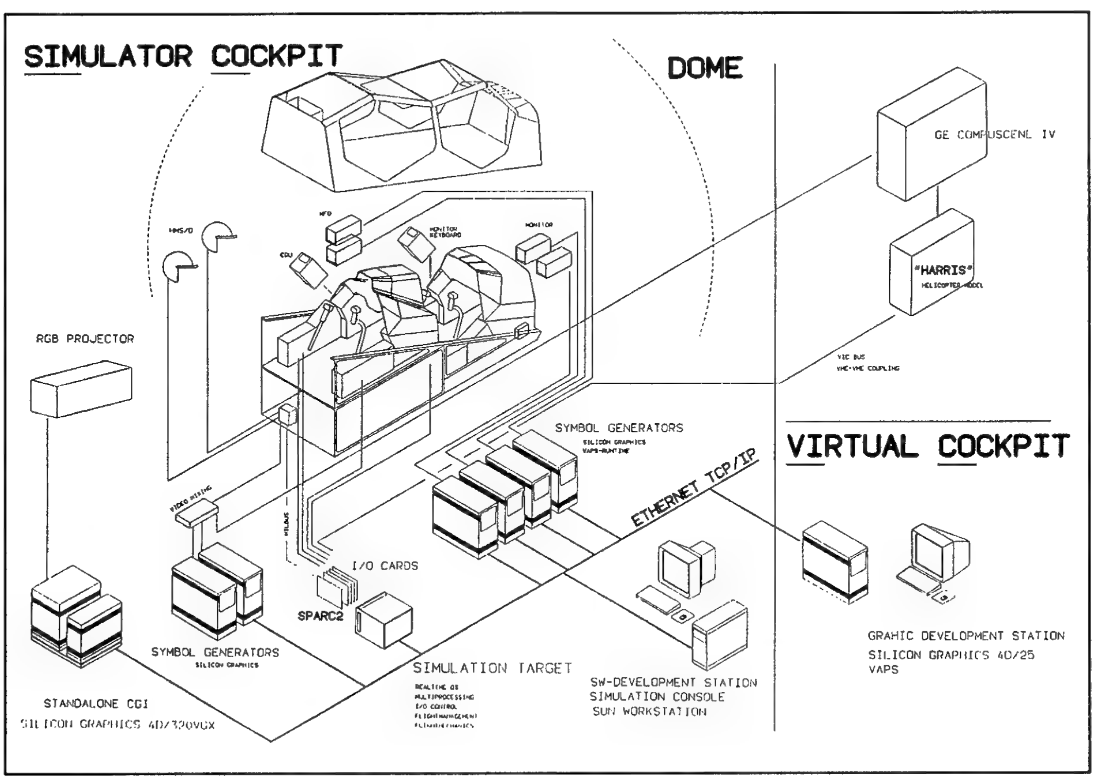

Figure1. Simulateur SIMCO

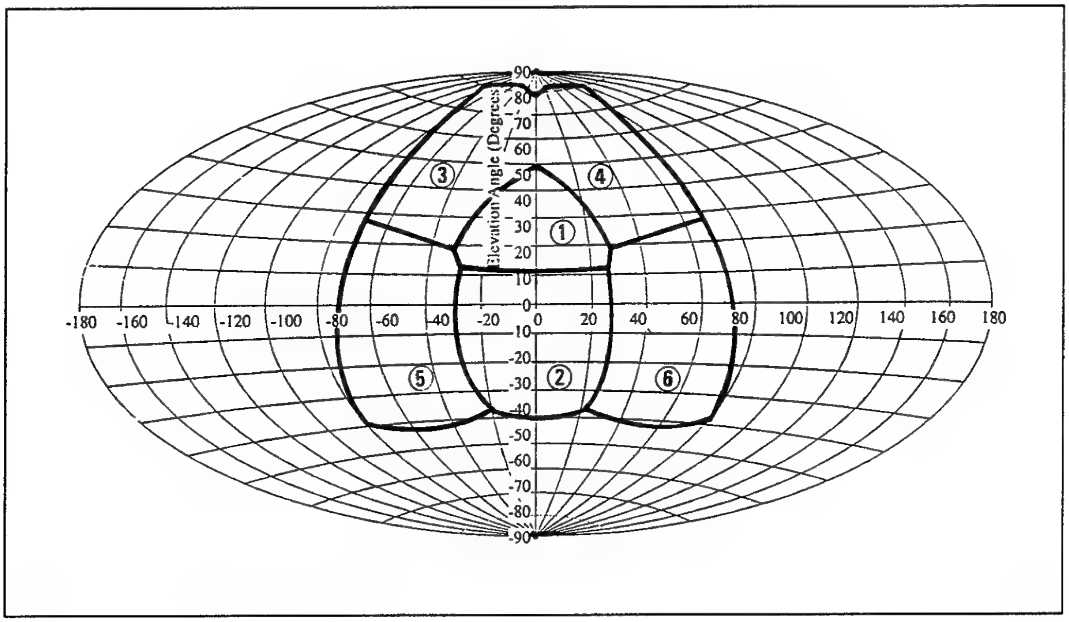

Figure 2. Champ de vision du dôme DASA

Figure 3. Vue de la simulation SIMCO (dôme DASA)

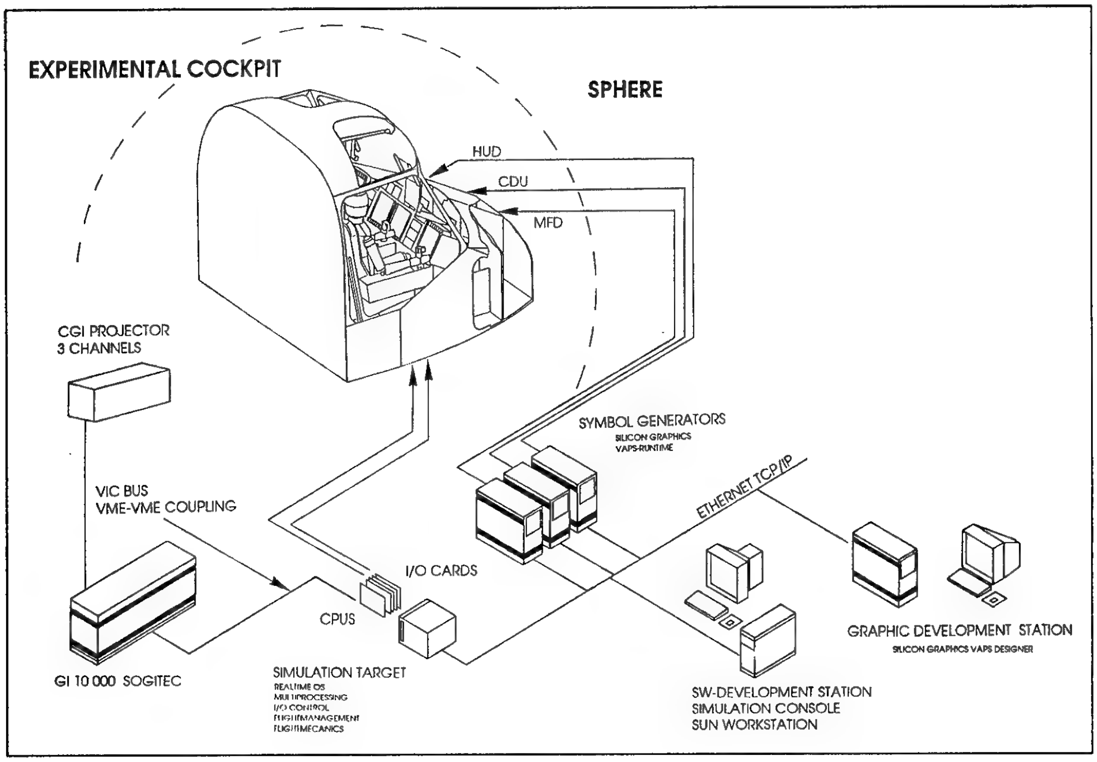

Figure 4. Simulateur SPHERE

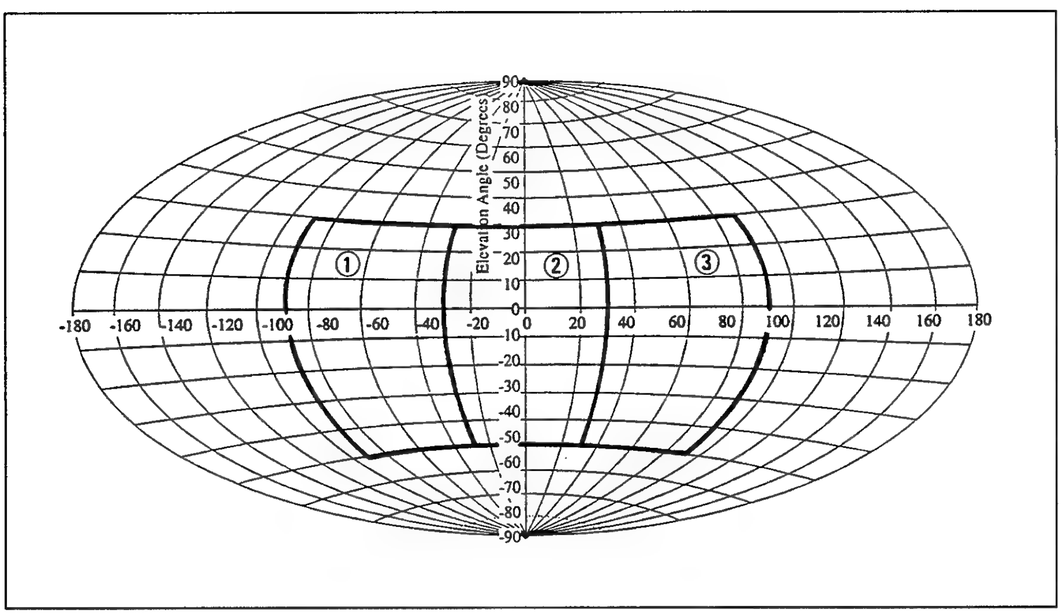

Figure 5. Champ de vision du simulateur SPHERE

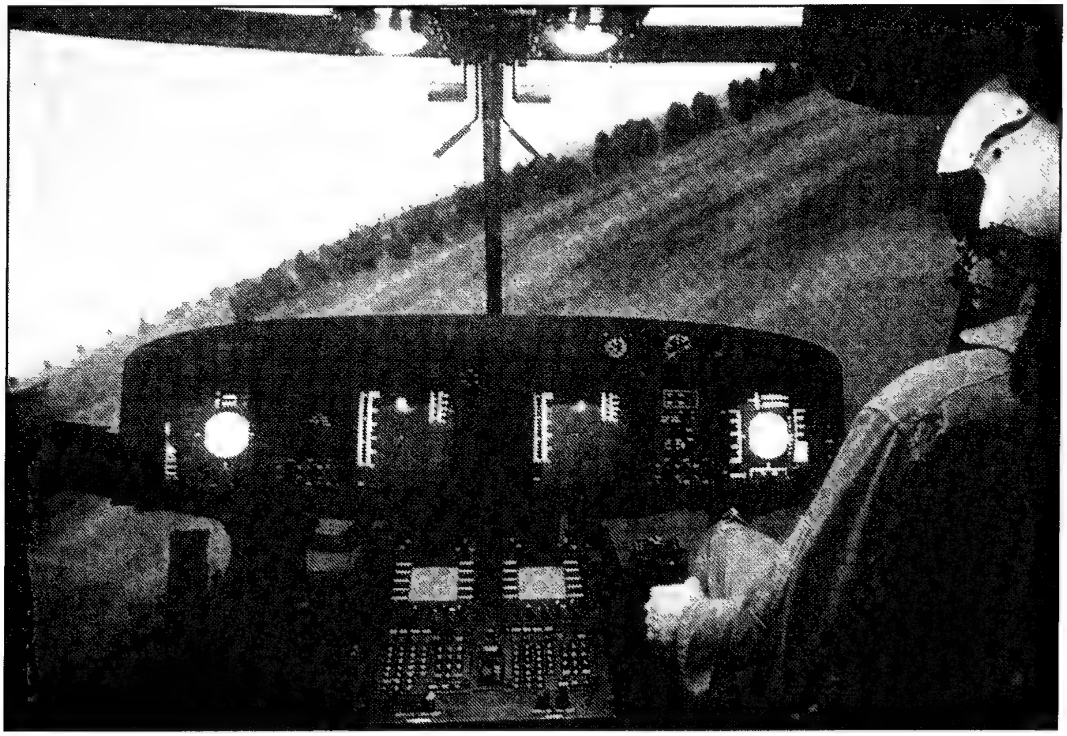

Figure 6. Vue de la simulation PFCS NH–90 (SPHERE)

Figure 7. Obstacle artificiel pour manoeuvre "Lateral Jinking"

Technological and Economical Limits Experienced for R&D Mission Simulation

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SUMMARY
This paper illustrates some significant lessons learned through R&D activities performed at the Flight Simulation Center of Alenia Aeronautica in Turin, highlighting experiences in Data Base Generation, Graphics and Graphics Prototyping, Particular Simulated Tasks and Integration of Dedicated Devices such as Target Projector and g-Seat g-Suit System.
For each specific mission task, the problems, solutions, alternatives and resulting system limitations involved in identifying the required system characteristics are discussed.

INTRODUCTION
In the R&D Mission Simulation, it is easy to run into technological and economical roadblocks. Consequently it is the best area to investigate and define the characteristics and the specifications of particular devices for specific tasks.

Design, prototyping, production and new versions development are the phases of the aircraft life and consequently of the associated simulator.
For each phase, the tasks to be performed are different, generating additional requirements for the existing simulation tools, which have to be tailored, upgraded or modified.
Simulation has achieved its highest engineering expression in the modern aircraft flight simulators.
Ground-based flight simulation increased its importance and its legitimate domain of investigation and application both as research and development tool and as a training aid.
Computer flight simulation is a development tool with unique capacity to develop and to evaluate design information during the whole life of the aircraft program.

Two simulators are considered in this paper:

- A/G mission AMX
- A/A mission EF2000

The first aircraft is well into production while the second one is in the prototype phase, consequently the two simulators are in different states of integration.
Different requirements emerge for these simulators, due to the different status of the programs and the different roles of the related aircraft.

AMX and EF2000 FLIGHT SIMULATORS
Two independent flight simulators are working in the Flight Simulation Center in Turin.
They are mainly structured following the same philosophy, but with some substantial differences, due to the different roles of the aircraft.
Both systems have:

. Cockpit on fixed base
. 30-feet inflatable dome housing the cockpit
. Projection system inside the dome
. Host computer and Special Purpose Computer (CIG, Graphics Work Stations, etc.)
. Control room

AMX Simulator
It is the oldest one and its configuration allows R&D and pilots training activities.
The cockpit is fully equipped with the real hardware (h/w) including the MIL-STD-1553 instrumentation.
The real HUD has an additional lens to collimate the simbology to the image on the internal surface of the dome.
The projection system is composed of three TALARIA Light Valve Projectors PJ5155 with standard lenses, located behind and above the pilot's eye, projecting a three windows image of 160° horizontal x 50° vertical: one high resolution channel (1 million pixels), two medium resolution side channels (0.5 million pixels each).
A Control Loading System is integrated with the stick for the simulation of powered and manual flight controls including hydraulic failures.
A pneumatic/electromechanical g-Seat/g-Suit system is integrated in the cockpit for tactile sensations.
A very simple sound system is implemented.

EF2000 Simulator
The cockpit is full equipped with commercial/ homemade and representative displays and real equipment such as:
- primary flight controls (stick, throttles, pedals) interfaced via MIL-STD-1553 buses;
- seat mock-up;
- console panels.

Paper presented at the AGARD FVP Symposium on "Flight Simulation — Where are the Challenges?", held in Braunschweig, Germany, from 22-25 May 1995, and published in CP-577.

The HUD symbologies are projected on the scenario by a CRT projector in the correct FOV to the pilot's eye.
The projection system is composed by three TALARIA PJ5155 equipped with wide-angle optics and located below the cockpit projecting three windows for a continous image of 190° horizontal and 50° vertical: high resolution in the central channel and medium in the side channels.

A dual slewable and zoom optics for independent targets is integrated with a LV9000 SIM projector. A Silicon Graphics workstation provides two independent target images.
The dual optics is able to project in any azimuth and elevation of the dome two targets controlled by either the second dome or through the control room console or by an "intelligent" software (s/w) program.

Data Base Generation

a - Generic data base limitations.
The image generators (IG) employed in the Alenia Aeronautica Simulation Centre (CIV and CIV-A) are able to display only data bases developed by means of Data Base Generation System (DBGS), an integrated combination of dedicated software and hardware tools (essential h/w: Sun workstation - Eikonix scanner - Summagraphics digitizing table).

A DBGS data base is a mathematical model of the entire visual scene available to the image generator; it usually represents some specific geographic area in the world, but it may also depict a generic area, provided it contains suitable visual cues for training on specific tasks. The base components of such data base are terrain and culture, that are, respectively:

- a network of triangular or quadrangular faces, matching the actual ground course, in as much detail as wished by the user;

- the representation of the most relevant three dimensional features, either natural or man made, present in the area of interest.

Besides, a data base is comprised of several data types loaded into the IG memories either at mission initialization or during a real time mission:

- Environment Data Blocks (EDB), of fixed size, containing the basic geometric description of:

  . static features - the majority of the data base, including terrain,surface culture, static 3-D objects;

  . moving models - separately controlled coordinate sets;

  . special effects - e.g. explosion, lightning;

  . universal features - features often instanced in the data base, such as trees and houses;

- EDB related data, such as collision detection and target data;

- light and color tables;

- texture data, needed to project raster images, acquired through a scanner, upon terrain or culture faces.

The previous data types, with the exception of moving models and special effects, are actually organized in two separate mathematical models: a coarse data base, active in the background, and a fine data base, active in the foreground. The two data bases are organized according to the following hierarchy:

- the most elementary unit is a square degree;

- each square degree is subdivided into coarse regions, rectangular in shape and uniform in size all over the data base;

- each coarse region is split into fine regions, whose size must be some even subdivision of the coarse region size, while their boundaries can be irregular, reflecting the actual terrain outline;

- eventually, each fine region is comprised of clusters, consisting of one or more terrain faces plus all surface culture insisting on them.

b - Italian D.B. generation: advantages, limitations.
At the beginning, data bases provided by the IG manufacturer were used, mainly the broadest one, representing the region of Lake Mead (USA) surrounded by a wide generic area. notwithstanding that the pilots who were trained in Alenia Simulation Centre found them not satisfactorily fit for realistic simulation.

The demand for a new data base, including the greatest possible area of Italy, sprang from the task of integrating a Mission Planner, developed by the Alenia Artificial Intelligence Laboratory, into the AMX simulation program.

Even Lake Mead data base was unfit: source data were not available, which prevented us from working out the simplified terrain and culture, strictly coherent with the data base itself, essential to the mission planner; in addition, it covered too limited an area, where the eligible way-points were too few and scattered for the

operative requirements of the planner itself.

Therefore, we chose to generate a brand new data base, covering a global area of sixteen square degrees (from 38N-14E to 41N-18E).

First of all, we had to face the limits common to all DBGS data bases due to IG memory and processing constraints, starting with the maximum on-line storage provided by both CIV and CIV-A (only 512 EDB's) and the maximum number of faces contemporaneously displayed, just 4000, comprised of terrain, surface culture and models.

Such limits involved the need for a careful, overall data base design.

For instance, the DBGS offers a choice of fixed or variable density terrain structure: while fixed density terrain yields explicit user control over terrain density, therefore a more regular form and a predictable load, variable density terrain provides a better fit of terrain triangles to the actual area modelled, through the generation of a less uniform structure.

Another critical choice is that of the coordinate system: as to the earth shape, one can select either flat earth with convergence or geocentric earth and also the units, normally feet, can be designated as centimetres to provide greater resolution.

However, no matter how careful the global design is, forcing the data base to stay within the IG processing constraints is a very complex task with many variables, such as the number of viewpoints, the number of channels and the field of view per channel, the activation range by feature type, the number of terrain clusters per coarse region, the predominant height and speed the data base will have to be flown at. Indeed, the IG updates the display 60 times per second: during each cycle, a lot of parallel computations must occur and be completed; in addition, most internal processing lists have limited length.

For instance, in dual viewpoint systems both viewpoints must share the same processing capacity so that the data density of each must be less. The data density can increase as the field of view is narrowed, since a smaller portion of the data would be visible; likewise, as activation ranges are reduced for coarse and fine terrain and for data at each level of detail, the data density can increase again. The number of fine detail terrain clusters per coarse region is critical to the priority processing time; a conservative number is 80 and an upper limit of 160 clusters/ coarse region should be observed.

The IG contains real time overload monitoring and automatic adjustments to correct overloads with degraded performance, however the data base should be designed to largely avoid overload conditions.

Indeed, non generic data bases are usually built starting from Digital Land Mass System (DLMS) data, generated from satellite and other aerial reconnaissance photos; these data include both terrain elevation grid data and overlaid cultural data, describing the location, size and main attributes of all significant features. Such data were available only for four square degrees at Level 1 standard (not including linear features), therefore all the remaining area had to be built from terrain contour lines and culture features digitized on the spot from 1:250000 pilotage charts.

This caused a lot of additional problems, which turned evident only eventually, while flying the data base, such as:

- mismatching of neighbouring degrees at the boundaries, due to mistakes in digitizing overlapping contour lines;

- generation of uneven terrain surface underlaying hydrographic features;

- inaccuracy in the resultant altitude and neighbourhood of particular way-points.

Such problems could be solved mainly by turning the terrain structure of the wrong areas into variable density, inside the overall fixed density terrain, correcting some of the contour lines and/or digitizing some new ones, inserting/ deleting some terrain triangles directly.

After all, a final check of the data base quality had to be performed in the dome to take into account the lower contrast and brightness and the different field of view generated by the projector system on a white screen; some peculiar colour matching suitable for the monitors often did not prove the best harmonization inside the dome.

c - Texturing requirements.
Cell texture generation is the process of capturing images, mainly drawings or photos, as cell maps and then associating the maps themselves with specific data base faces; the process can be split into three steps: capturing a source image, generating the related cell map, placing the map over one or more faces.

In order to get a suitable cell map, the modeler usually needs to modify the initial result, whatever its origin, increasing or sweetening its contrast, keeping only a part of it, combining it with a different picture, inserting or getting rid of some details, eventually smoothing the matching of two opposite edges (right/left or upper/lower), if the image has to be repeated where projected.

Afterwards, to position a cell texture map on a face, several items of information are required:

- rotation, offset and scaling : orientation, location and size of the map;
- translucency: relative opaqueness, transluce, or transparency of the cells;
- modulation: contrast range of the cells;
- edge control: bits that determine the wrap-around conditions and the edge blending options for the cell textured face; the option of wrap around is provided so that a very large face may have a pattern continuous up to the limits of its edge.

The overall process is quite long and demanding, moreover the texture can be actually tailored only while flying: for instance, broad translucent areas may cause overload only when inserted inside regions already too rich in details, which cannot be realized a priori.

Despite a good deal of efforts, black-and-white texture may fail its aim of making the landscape depicted true-life, especially as to large surface culture; however in our data base the worst effect, highly annoying, was attained by the terrain itself, which was satisfactorily solved by changing the colour of terrain faces, choosing automatically one out of ten close tonalities of brownish.

d - 3D Objects requirements.
A **model** is a group of faces and possibly point lights stored in a model library and subsequently placed in the environment as a group, as far as channel assignment, priority and level of detail decisions are concerned; any combination is valid, provided it does not exceed a single EDB limit.

A maximum of 32 models into some meaningful arrangement, named **model complex**, can also be stored on the model library and therefore placed in the data base by simply specifying its location.

Eventually, a **supermodel** is an assembly of up to 8 individual models defining a single moving model, such as an aircraft carrier or a fighter. Each part of a supermodel is called a partition and is stored under its own name on the model library; all partitions are modelled relative to a single origin, usually the resulting supermodel's center of gravity.
It is quite intuitive that supermodels are the most demanding 3-D features, but some static models in our data base proved challenging, too: for instance, 3-D cities, not supplied by DBGS, were implemented as properly textured raised forests, while small clouds were accomplished as trees with huge, invisible trunks and white, translucent textured leaves.

Much care was given to **target areas**, selected way-points surrounded by a whole bunch of objects to make them recognizable and true-life: for a city, streets (highway, if any), railroads, crossroads, bridges; for an airport, the tower, large buildings, bushes, trees, groups of houses; for a lake, hotels, trees, gardens and so on.

e - Time & Cost
The generation on site of the data base described above required the efforts of a dedicated person for two years and a half, six months of which thoroughly devoted to learning how to exploit the subtlest features of DBGS.

Digitizing and **testing** largely proved the two most time-consuming operations; while the former could have been saved, provided the DLMS data had been available, there was no way to avoid the latter, since only the pilots' comments could allow to realize which details were actually essential to the simulation goals.For instance, the choice of colouring the terrain faces, the insertion of objects in front of each airport end, the effort to cover large culture areas with several different texture patterns so to make the data base lively even where objects and further details were lacking, were all answers to needs expressed by the pilots under training.

The testing activity was also the most expensive item: each significant modification required the use of both the image generator stand-alone and of the simulator with a pilot in the loop, so summing up to a whole bunch of hours.

We would not be far from truth stating that digitizing and processing contour lines and culture took about one year, while the second year had to be devoted to correcting and improving the data base.

In addition, the generation of moving and fixed models took only about six months, since some general model libraries had been supplied by the manufacturers.

For sure, a new-generation device, able to actually take care of the image generator real-time limitations, would have helped in cutting costs, saving at least the stand-alone tests, while colour texture would have reduced the need of mixing different patterns.

Operational Issues
Simulation tasks often require trade-off between different possible technical solutions in order to achieve the best available realism without increasing costs beyond acceptable levels;
therefore, the most careful attention must be payed to all those features of the visual system, the cockpit (controls and displays), the motion system (if required), the scenario, needed to present a true-life reproduction of the environment experienced by the pilot during an actual flight.

Such goal becomes vital in case of peculiar environmental conditions, such as **low level night flying**, or high demanding tasks, e.g. **formation flight** or **air-to-air refuelling.**

Low Level Night Flying
The field of view (FOV) of the overall background image stays 160°h x 50°v, but also the middle channel is allowed just medium resolution (1024x512); a fourth channel (1024x512), associated to a second viewpoint, is projected on the cockpit multifunction display.

Such solution, alongside the level of detail and the image resolution, proved effectual to simulate the tasks related to the air-to-ground role typical of the AMX aircraft, providing also good response to the secondary air-to-air tasks simulation.

One of the most demanding tasks in air-to-ground attack role, low level flight at night or in marginal weather conditions has become more and more a frequent task in modern flight operations, during which sophisticated surface-to-air weapon systems are to be faced.
Training a pilot in performing the procedures required by such a mission involves the simulation of the different electro-optical (E/O) sensors used by the pilot as flight support:

- Navigation FLIR
- Targetting Pod
- Night Vision Goggles (NVG).

Navigation FLIR
In order to simulate the operational use of a raster/stroke HUD with navigation FLIR, the IG representation of the external world has been elaborated, providing a monochromatic (32 levels of gray) image similar to the one supplied by an IR sensor.

The typical raster/stroke HUD FOV limits the image presented to the pilot to 30°x20° in boresight direction; this restricted FOV is not obtained via software, instead an appropriate template has been elaborated so to hide the IG image but for the FOV corresponding to the HUD.

This solution allows us to quickly restore the original 160°x50° FOV when required (e.g. when simulating the use of NVG) avoiding modifications of the IG parameters during the simulation session and the related time consuming procedures.
The monochromatic image (Sensor Color Table) of the IG is sufficient to satisfy the task involved without implementing a very sophisticated and expensive Sensor Data Base.

Targetting Pod
Simulation of the typical IR steerable head of a laser designator pod requires the use of the IG fourth channel, displaying the same monochromatic standard of the remaining IG channels.

The line of sight (LOS) of the fourth IG visual channel, instead of being fixed as for the remaining three channels, is steerable; steering modalities are the same of those envisaged for the real targetting pod (either in automatic or in manual mode), thus allowing an accurate simulation of the targetting pod seekerhead aiming procedure.

The fourth channel viewpoint position is the same of the seekerhead pod installed on the aircraft (fuselage centerline station); moreover,it is possible to increase/decrease the channel FOV in order to simulate even the real pod zoom capability.

Night Vision Goggles
Simulation of NVG operational use requires the evaluation of several aspects related to the image presentation and also, not a less critical factor, to the equipment bulk and weight.

Several solutions can be worked out, taking as a standpoint the use of a typical GEN III NVG equipment and the specific simulation tasks.

At first, the use of a steerable projector was evaluated, so to visualize an appropriate image of adequate FOV (45° circular for each eye, typically) in the pilot's area of interest, therefore simulating the "tunnel" effect due to the reduced NVG FOV.

In order to lower costs, the pilot FOV was afterwards reduced, so allowing only the required portion of the whole 160°x50° IG image to be seen at each moment; this was achieved opening two port-holes corresponding to the pilot's eyes in the transparent visor of a standard HGU-2P flight helmet, by means of an appropriate template. For the same reason, we chose also to disregard the pilot's physical stress, focusing only on the visual aspect of NVG operational use, no matter how bulky the used device turned out to be.

Using the monochromatic table described above for the FLIR simulation proved the least demanding, though satisfactory, way to show the NVG vision on the IG.

The final result has proved effectual in simulating the obstruction and the image quality of the NVG; visibility inside the cockpit is similar to the one allowed by the use of a typical in-line optical scheme.

Both introduction of NVG compatible cockpit lighting and masking of cockpit light sources

proved unnecessary and also simulation of the NVG image blooming due to intense light was not deemed a major factor and therefore discharged.

Besides, simulation of a night-time environment and of the related NVG/FLIR sensors imagery relaxes the requirements for depth, definition and speed cues, otherwise mandatory in case of low level flight simulation task.

Visibility was adjusted to allow recognition of ground targets at the distances typical of the relevant E/O sensors.

Alongside the E/O sensor, simulation of a multimode radar is an important issue when assessing AMX night attack version capabilities.

Multimode Radar
Simulation of a multimode radar is aimed to providing the pilot with the workload he has to face during actual radar operations.

Thanks to the specific simulation tasks, we could spare developing complex radar models, focusing all our efforts in generating a realistic simulation model, furnished with several different modalities:

- A/A Ranging
- A/S Ranging
- Ground Mapping
- Terrain Avoidance
- Contour Mapping.

Since A/A attack capability was not to be assessed, no further A/A mode has been developed.

The major effort in this simulation is the landmass definition, to be performed according to the IG database; in this way it was possible to include correlated returns of ground tracks.
The landmass simulation is possible thanks to the use of a VGXT 420 workstation.
The radar returns are presented inside the cockpit on a proper multifunction display upon pilot request; radar fixing procedures are available to the pilot in Ground Mapping Mode.

A dedicated control panel is included inside the cockpit for radar modes management, antenna tilt and gain control; appropriate HOTAS controls are allocated as well.

The radar simulation provides effectual aid to the flight in night-time or marginal weather condition, allowing the pilot to recognize waypoints and target locations out of the E/O sensors range, exploiting navigation and attack accuracy whenever passive target detection is not a critical factor.

Cockpit
The realistic cockpit reproduction in terms of controls and displays available to the pilot is mandatory for simulation effectiveness.
Response of each aircraft system should be replicated in the most precise way.
When a new system architecture has to be evaluated, modifications to the cockpit layout are often necessary, expecially if the Man Machine Interface (MMI) is heavily involved.
In such case the introduction of an additional display is needed.
A rapid prototyping front panel of the cockpit would be more beneficial in terms of minor h/w modification and quickest representation of the new modification.

Wide angle HUD symbology is generated by a Silicon Graphics workstation linked in real time to the simulation computer and projected inside the dome superimposed to the IG image, while the real conventional HUD available on the flight simulator is inactivated.

Formation flight
This task is performed in the AMX simulator as well in the EF2000 one, exploiting different conditions.

In the AMX simulator the h/w key elements are the **visual system**, the **g-seat/suit** system and the **sound system**.

The visual system is limited in horizontal to 80° left and right, which compels the second aircraft to be displayed inside a strict FOV.

The g-seat/suit system helps the pilot to control the aircraft in minimum movements at high frequency, providing the tactile sensation so significant for such task.

The sound system is an additional feed-back giving several aural cues related to the dynamic of:

- aerodynamic noise;
- the engine RPM variation;
- APU noise / ECS noise;
- landing gear touch-down;
- wheels rolling on the runway.

No motion system is present, but the control of the aircraft in all possible formation flight configurations proves satisfactory and feasible: actually, the worst drawback is just the limitation of the visual scene FOV, which will be partially solved installing a slewable optic behind the pilot's eye, capable of projecting a second aircraft and the background inside a window of 50°hx35°v in azimuth and elevation.

As highlighted before, in the EF2000 simulator

the characteristics of the hardware are different: neither a g-seat/suit system nor a sound system are available, while **a wider FOV of the visual scene** and a new generation **target projector** are integrated.

The target projector system consists of a dual indipendent high resolution, light-valve target optics, complete of zooms and shutters, projecting two circular windows ranging from 20 to 7 degrees; the two target images, produced by a Silicon Graphics workstation and therefore thoroughly independent from the CIV, can be projected both instead of the IG models and wherever in the dome such models cannot be displayed.

A correct evaluation of the conditions where either the IG or the Silicon Graphics targets have the better effectiveness has not been yet investigated in deptht: it depends on the distance, the relative attitude of each target, the weather conditions and the time of the day.

Due to the engine and flight controls of the EF2000, performing close formation flight is more difficult than in the AMX simulator; according to the pilots' analysis, to overcome the problem the availability of the sound system would be much more essential than the one of the g-seat/g-suit system. In order to verify such hypothesys, different assessments in both simulators have been performed varying the cueing environment:

a) AMX simulator without sound system;

b) AMX simulator without g-seat/suit system;

c) AMX simulator without either sound or g-seat/suit system;

d) EF2000 simulator with one, or with two targets.

In the first three cases, a target controlled by a dedicated station in the control room was displayed in the scene as a wingman, once on the left, once on the right and once in front as a leader.
The target's manoeuvres were selected starting with a simple linear velocity, then smooth left and right turns with pre-calculated roll angle (30°, 45°,60°), eventually the complete dynamic of an aircraft with the same performances of the manned simulated one.
In the first case, the pilots experienced difficulties during the very close formation flight, but after several attempts they proved able to perform the task, within adequate criteria.

In the second case, after a period of familiarization with the alterated cues the pilots were able to fly in formation with gentle manoeuvring. However some degradation was experienced with more rapid manoeuvres, especially lateral ones.

In the third case, the lack of both systems caused a very difficult control of the aircraft in fine adjustments, but again, after a certain amount of attempts the pilots were able to reach a satisfactory level of aircraft control.

Moving into the EF2000 dome, the pilot found himself in the same situation as the third case of the AMX (neither sound nor g-seat/suit system), but for the implementation of a slewable projector of two indipendent targets. The results were comparable to the third case experienced with the AMX simulation.

A formation flight with two independent targets has been tested in different configurations and in any value of azimuth and elevation of the targets. The limitations of this configuration are highlighted in the 20°maximum FOV of the target image outside the background scene (190°hx50°v). This means that an aircraft with the dimensions of a fighter like the EF2000 can be completely displaied not closer than 40m.
No major differences from the results obtained in the AMX simulation have been highlighted, apart from the different behaviour of the aircraft in terms of flight control system.

In-flight refuelling
Another task experienced in both simulators is the in-flight refuellig.
The configuration of both simulators has been described above.
In order to give the visual cue of the probe attached to the manned simulated aircraft, a model of it has been generated in the IG and displayed in the scene as a fixed part of the "box" of the own aircraft (the own aircraft is designed syntethically as a box).

The probe has been depicted as a model composed by 6 EDBs using about 60 faces getting the data of the AMX real one with the farthest point fixed at 2m forward and 1m to the right in front of the pilot.
The tanker is a Boing 707 TT used by the Italian Airforce equipped with three baskets generated by the DBGS as well.
The dynamics of the baskets' length and the turbulence behind the tanker have not been simulated.
To simplify the task to be performed, the tanker flies at a constant altitude and velocity, positioned at half mile in front of the pilot.
The image quality and the visual cue of the probe are realistic even if the 3-D is absent and the tanker model is very close to the real one, complete of shading, texture and light points.

Flying towards the tanker is a task that does not involve difficult controls, but as soon as the

fighter gets close to the tanker and the pilot starts engaging the basket with the probe a very uncomfortable feeling appears, causing the task to abort after several attempts.
Such failure is due to two major reasons:
- lack of vestibular cue;
- lack of 3-D visual cue.

The vestibular cue helps controlling the aircraft close to the tanker in the fine adjustments especially around the longitudinal axis, when the tanker is above and the basket is less than 10 meters far from the probe.

The 3-D visual cue plays an important role, when the objects in the scene are closer than 20 meters. The sensation of the in-flight refuelling in 2-D is comparable to a flat picture in which understanding the object order in depth is impossible.
The final result is a very difficult task, risking to engage a pilot coupling mode in longitudinal axes.
In order to partially mitigate such unwanted effect, an artificial translucent disc has been drawn and added on the top of the probe.
This disc, the same size as the basket, helps the pilot in better understanding the basket position relative to the probe.
Some improvment has been obtained, but the task still remains very difficult, successful only after many attempts.
Some Airforce, for example, use special facilities to train pilots to this specific task:
their simulators reproduce an h/w scaled mock-up tanker and the probe is a 1:1 scale mock-up.
With a special optic system it is possible to combine the view of the h\w (probe and tanker) with the background scene, generated by an IG.
The 3-D image so got succeeds in training properly without the motion platform stimulating the vestibular system.

Graphics

The graphic symbologies generated by the workstations connected with the real-time simulation are dedicated to the onboard Multi Function Display System and to the operator/instructor console Color Monitors.
These graphic representations are mainly 2-D, therefore not very demanding for the workstations CPU; however, the graphic processor is heavily loaded due to the high image refresh rate.
In the Alenia Flight Simulation Center, Silicon Graphics workstations connected in LAN on Ethernet with TCP/IP protocol are being used.
Three of these are high performance, capable to generate complex graphics such as A/G RADAR representation, two independent targets, colour maps and synthetic interactive scenario.
C language under Unix system is used to generate the graphics running at different rates, depending on the task.
HUD, AOI, dual targets and others are high performance graphics running at 30 - 60 Hz with a time delay of about 50 ms.

The workstations have the possibility to send video signals in different standards compatible with the display system in the cockpit, in the dome and in the control room: the most used standards are 30 Hz interlaced, PAL, NTSC and 60 Hz not interlaced.
Particular attention is devoted to the monitoring in control room; the aircraft behaviour is represented in real time at 30 Hz in terms of attitude, surface movements, stick position, engine values, landing gear movements and other dedicated visualizations.
Related to the system modelling and relative failures, a monitor is devoted to the graphic representation of the functionality of general systems such as electrical, power and secondary power system, completed of animation of these systems components during the normal and failured behaviour.

The limits of this graphic network system are determined by the number of the workstations working at the same time. For different tasks and different configurations, different allocations of the workstations have to be defined in order to split these between the AMX and EF2000 flight simulators, both using video switches controlled by the pilot in the cockpit and/or by the control room.

Conclusions

Several technological limitations of the existing simulators are evident, depending on the tasks to be performed.
Using an R&D simulator means to be able to touch many aspects of the simulation spectrum:
- trade-off evaluation between operative configurations;
- ground and general handling simulation;
- handling simulation with manual flight;
- failures simulation and analysis of the pilot's reactions;
- emergency procedures;
- data bases and interactive scenario generation and integration;
- operational mission simulation, including phases like A/A combat, formation flight, in-flight refuelling;
- human engineering assessment;
- development of Crew Assistant System;
- simulation engineering development.

During all these tasks is easy to impact into the difference between the reality of the simulation and the reality of the real world.
Many trade-off analyses and compromises have to be done task by task and different solutions have to be chosen case by case depending on the architecture of the simulator in use and eventual improvements that can be implemented.

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LIST OF ABBREVIATIONS

A/A	Air-to-air
A/G	Air-to-ground
APU	Auxiliary Power Unit
DBGS	Data Base Generation System
DLMS	Digital Land Mass System
DMA	Defence Mapping Agency
ECS	Environment Control System
EDB	Environment Data Block
FLIR	Forward Looking Infrared
FOV	Field Of View
HOTAS	Hand On Throttle and Stick
HUD	Head Up Display
H/W	Hardware
IG	Image Generator
IR	InfraRed
LOS	Line Of Sight
MMI	Man Machine Interface
NVG	Night Vision Goggles
S/W	Software

Utilisation de la simulation pour la conception du SNA du Rafale

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1. SOMMAIRE

Dans cette présentation élaborée conjointement par Dassault Aviation et le Centre d'Essais en Vol (CEV), nous indiquerons d'abord les innovations importantes adoptées dans la démarche de la conception du Système de Navigation et d'Armement (SNA) de l'avion Rafale et en particulier le rôle fondamental de la **simulation**. Nous montrerons ensuite la synergie existant entre Dassault Aviation et le CEV dans la définition des besoins de cette simulation, dans le choix des modèles et des moyens qui la composent et dans son utilisation par l'*architecte industriel* et l'Etat.

Quelques précisions sont nécessaires avant d'entrer dans le vif du sujet :

- dans le programme Rafale, Dassault Aviation est l'*architecte industriel* du SNA
- le CEV est, au sein de la Délégation Générale pour l'Armement, l'organisme étatique expert pour les essais en vol ainsi que la mise au point des matériels aériens et systèmes embarqués militaires
- la simulation désigne ici la simulation pilotée

2. LA SITUATION AU DEBUT DU PROGRAMME RAFALE

Par rapport à celle des systèmes des différentes versions du Mirage 2000, la conception du système du Rafale est sans commune mesure. En particulier, la maîtrise de la définition de son SNA, pour prendre en compte une expression de besoin très ambitieuse, a nécessité un changement et des innovations dans la démarche de conception. En effet, plusieurs difficultés fondamentales se sont nettement imposées dès le lancement du programme :

- la complexité de l'analyse technique du besoin opérationnel et notamment la polyvalence demandée au système,
- le niveau d'intégration du système qui en découle, pour ne pas augmenter la charge de travail de l'équipage que ce soit dans le cadre d'une version monoplace ou biplace,
- la maîtrise des coûts et des délais

3. LES INNOVATIONS DANS LA DEMARCHE DE CONCEPTION

Pour faire face à de tels enjeux et surmonter ces difficultés, une démarche totalement nouvelle a été adoptée pour permettre de maîtriser la conception du système d'armes.

3.1 La vision avancée système

La conception du SNA Rafale (l'architecture matérielle et logicielle, les règles générales, la définition de la cabine et de l'interface pilote système) n'était plus compatible d'une démarche consistant à additionner les fonctions opérationnelles après les avoir définies séparément. Il a fallu au contraire se projeter dans l'avenir et bâtir, le plus tôt possible, une **vision avancée du système** prenant en compte l'ensemble des fonctions opérationnelles et techniques, ce qui a permis de définir leurs priorités respectives et les principes de leur mise en oeuvre. Il est par exemple fondamental de considérer tous les différents capteurs destinés à équiper l'avion à l'issue de leur développement, ceci de façon à établir les règles de leur partage par les fonctions utilisatrices, les logiques de gestion ou de ralliement à leur appliquer et les lois d'association ou de fusion des informations qu'ils fournissent en vue de leur présentation à l'équipage. Il faut également que cette vision à terminaison comporte une première définition de la préparation de mission, qu'elle permette une coopération entre plusieurs acteurs interactifs et qu'elle intègre l'utilisation du système Rafale au sein de réseaux de contrôle et de commandement. Ainsi, la connaissance des différentes conduites de tir envisagées permet de définir l'architecture la mieux adaptée pour optimiser les ressources matérielles et logicielles du système, tout en privilégiant la modularité et l'évolutivité nécessaires aux besoins opérationnels futurs. De cette vision avancée établie très tôt dans le développement, sont ensuite déduites les versions intermédiaires du système qui, pour des raisons techniques et économiques, est réalisé progressivement.

3.2 Le groupe de conception système

Pour concevoir cette Vision Avancée Système et la faire vivre, il faut savoir « regarder loin » et avoir les « bonnes idées » tant sur le plan opérationnel que sur le plan technique. Ce travail

Paper presented at the AGARD FVP Symposium on "Flight Simulation — Where are the Challenges?", held in Braunschweig, Germany, from 22-25 May 1995, and published in CP-577.

est réalisé par un Groupe de Conception Système, composé de pilotes d'essais et d'ingénieurs de façon à prendre en compte à la fois les aspects ergonomiques et les aspects techniques. Le rôle de ce groupe est de concevoir à partir des spécifications techniques de besoin, un système utilisant les techniques et les technologies émergentes pour satisfaire des performances exigeantes mais qui doivent rester compatibles de la charge de travail des pilotes et de la fiabilité indispensable à leur sécurité. Ainsi, à partir du dossier de construction système définissant les grandes orientations de la solution retenue (architecture et premier dimensionnement des ressources nécessaires), ce groupe de conception conduit et oriente les travaux des équipes spécialisées en charge du développement et de la réalisation du système.

3.3 Des outils : la simulation et le centre d'intégration hybridable

La démarche de conception ainsi adoptée pour le Rafale permet de maîtriser le développement du SNA, à condition de s'assurer que la Vision Avancée Système, d'une part répond aux besoins opérationnels et d'autre part est techniquement réalisable. Il apparaît ainsi nécessaire que le travail de définition réalisé puisse être représenté et utilisé par les pilotes, d'où le besoin d'une simulation temps-réel. Ceci d'autant plus que la documentation traduit mal pour les pilotes les aspects de superposition des fonctions opérationnelles, mises en oeuvre par des fonctions techniques.

L'approche sur le dimensionnement et la faisabilité technique est initialisée par une première estimation des ressources techniques et budgétaires nécessaires à sa réalisation. Les allocations qui en résultent sur les ressources les plus critiques (charges de calcul, volume mémoire et débit d'informations sur les bus) sont ensuite affinées et recalées par un rebouclage permanent. Un accord entre Dassault Aviation et les réalisateurs du logiciel embarqué permet d'exercer un contrôle de ces ressources. Le produit final qui sera utilisé par les pilotes opérationnels est ainsi le résultat de choix et de compromis; il faut donc permettre aux pilotes, aux ingénieurs et aux décideurs de faire ces choix à bon escient, ce qui renforce le besoin de la simulation. Pour cela, la simulation est développée avec le souci de représentativité sur le double aspect d'un environnement réaliste pour placer le pilote dans les conditions suffisantes d'appréciation et d'une architecture (en particulier le découpage fonctionnel et le respect des interfaces aux bornes des équipements) déduite de celle du système réel.

Pour concrétiser ce besoin, le **Centre d'Intégration Hybridable** (CIH) a été crée et installé au sein du bureau d'études de l'*architecte industriel* pour accueillir le maquettage du SNA du Rafale. Il s'agit d'un outil qui permet de montrer une image informatique du comportement du système dans un environnement représentatif simulé. Lancé en 1989, il est opérationnel depuis la fin 1992, date où a été présentée la première image informatique complète, appelée Vision à Terminaison du SNA du Rafale. Le CIH est organisé de manière à favoriser le travail en synergie des principaux acteurs de la définition, c'est à dire :

- les pilotes d'essais car la cabine et son environnement visuel respectent les règles ergonomiques principales de la cabine du Rafale. Les pilotes peuvent donc se prononcer sur l'utilisation du système à partir de son image informatique animée en temps réel et juger des retouches (simplification, optimisation) de la définition initiale qui évitent de coûteuses remises en cause ultérieures,
- les ingénieurs concepteurs : la modélisation temps réel du système respecte le découpage en équipements et en grands modules logiciels (d'où la dénomination du Centre d'Intégration Hybridable), ce qui permet aux ingénieurs de s'assurer des ordres de grandeur des principaux dimensionnements,
- les responsables étatiques du programme qui, grâce à la disponibilité d'une simulation similaire au CEV (cf. paragraphe 4), disposent avec une anticipation suffisante des éléments de choix des compromis techniques et budgétaires.

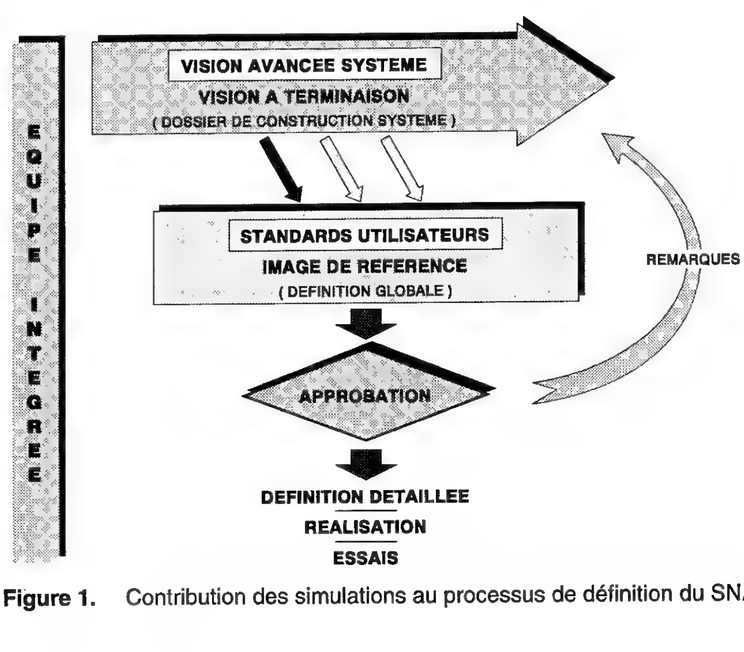

Figure 1. Contribution des simulations au processus de définition du SNA

3.4 Le travail en équipe intégrée

L'établissement, dans les phases amont du programme (environ dix ans avant le terme de son développement), de la Référence du système à terminaison nécessite de s'assurer de son adéquation aux besoins des pilotes opérationnels. Ainsi dès le travail de conception ceux-ci sont associés aux choix de base ; au fur et à mesure que la définition se précise et en particulier lorsque des compromis s'imposent pour tenir compte de la faisabilité technique, leur avis est indispensable.
La simulation est l'outil privilégié de ces différents travaux et comme nous le verrons par la suite, le travail en équipe intégrée, tantôt sous responsabilité industrielle, tantôt sous responsabilité étatique, est systématiquement mis en oeuvre.

3.5 Approbation de la définition avant réalisation des matériels et des logiciels

La vision à terminaison est plus ou moins précise suivant qu'elle correspond à des fonctions déjà maîtrisées sur d'autres avions. Elle va cependant permettre d'établir l'organisation du système : utilisation nominale des ressources par chacune des fonctions et règles de priorités entre elles. Une fois ces grandes lignes tracées, une définition globale est établie pour les fonctions dont la réalisation est demandée en priorité dans les différentes versions successives du système : les standards utilisateurs. Pour chacun d'eux, une **image de référence** de la définition est réalisée. Celle-ci est systématiquement soumise à l'approbation de l'Etat avant réalisation des matériels et des logiciels par les industriels coopérants du programme (voir Figure 1).

4. CONSTRUCTION ET EXPLOITATION DE LA SIMULATION - SYNERGIE DASSAULT AVIATION - CEV

4.1 Introduction

Nous l'avons déjà précisé plus haut, dans le cas d'un système complexe comme le SNA Rafale, l'analyse du besoin opérationnel et l'adéquation du produit final à celui-ci sont des défis majeurs. L'Etat et l'industrie doivent y répondre, chacun dans son domaine de compétence, en privilégiant le dialogue et la collaboration constructive. En particulier, l'industriel responsable de la définition du SNA ne pourrait pas se passer de la plus-value apportée par les futurs utilisateurs dans les phases de conception, notamment au niveau de la rédaction des spécifications globales servant de base à la réalisation, et chaque fois que des choix importants sont à faire, surtout dans les domaines touchant à l'emploi du système.
Pour mettre en forme cette plus-value, une organisation des travaux de définition a progressivement été mise en place avec le concours des partenaires industriels et étatiques. En particulier, le CEV et l'*architecte industriel* travaillent avec une synergie que nous allons préciser dans cette seconde partie, en s'intéressant plus particulièrement aux travaux relatifs aux simulations pilotées.
Tout d'abord, nous rappellerons les rôles respectifs de Dassault Aviation et du CEV, puis nous décrirons la méthode de travail. Le développement et l'exploitation des simulations pilotées seront ensuite exposés de façon plus précise.

4.2 Rôle de Dassault Aviation

Architecte industriel du programme Rafale, la société Dassault Aviation a la responsabilité de la cohérence d'ensemble du système d'armes. Elle est responsable de la définition de la cabine et de l'interface homme-système. Elle doit **maîtriser** cette définition (adéquation au besoin, respects des coûts et des délais) et notamment s'assurer en permanence de la **faisabilité** de ce qui est proposé. Dans cette optique, Dassault Aviation s'est doté de moyens et a mis en place des méthodes particulières dont les enjeux ont été présentés en première partie de ce document.

4.3 Rôle du CEV

De façon générale, le CEV est au sein de la Délégation Générale pour l'Armement (DGA) l'organisme expert pour les essais en vol ainsi que la mise au point des matériels aériens et systèmes embarqués militaires. Le CEV dispose d'un centre de simulation, situé sur la base d'Istres, au coeur des essais en vol industriels et étatiques, ce qui permet de profiter d'une synergie apportée par la confrontation entre travaux de simulation et vols d'essais.
Dans le cadre du programme Rafale, le CEV est responsable d'une partie des travaux relatifs à l'interface homme-système relevant de tâches étatiques. En particulier, il assure la synthèse des avis formulés par les représentants de l'Etat et est responsable des évaluations en vol et en simulation pilotée. A cette fin, des simulations Rafale ont été mises en place au CEV, et ce dès le début du programme. Profitant de moyens de simulation importants et de sa situation au coeur des essais en vol, cette simulation étatique permet un travail approfondi en contexte opérationnel et une utilisation intensive en soutien aux essais en vol. Elle est un des outils à la disposition de la direction de programme pour la maîtrise du développement.
L'utilisation complémentaire des différents moyens de simulation du programme dans le processus de développement système peut-être résumée sur le schéma présenté en Figure 2.

4.4 Méthode de travail et organisation des travaux

Pour rendre plus efficace le dialogue entre l'Industrie et l'Etat, le travail en "équipe intégrée", tant au niveau des ingénieurs que des pilotes, est privilégié pour l'ensemble du programme Rafale, sans pour autant diluer ou confondre les responsabilités de chacun. La simulation pilotée, image dynamique du système d'armes et outil de dialogue privilégié pour les principaux acteurs de la définition n'échappe pas à cette règle.
Pour mémoire, les essais en vol du programme Rafale, font l'objet d'un protocole signé entre l'Industrie et l'Etat, qui prévoit sa participation active dés la phase de mise au point chez le constructeur.
De la même façon, une organisation des travaux de simulation pilotée prévoit un fonctionnement en "équipes intégrées" à deux niveaux:

- cohérence technique simulateurs (Equipes CEV/Dassault Aviation/coopérants)
- travaux de définition système (Equipes Etat/Dassault Aviation)

Un ensemble de documents définit les responsabilités (notamment pour la conduite des essais, la gestion courante et les servitudes) et les règles applicables.

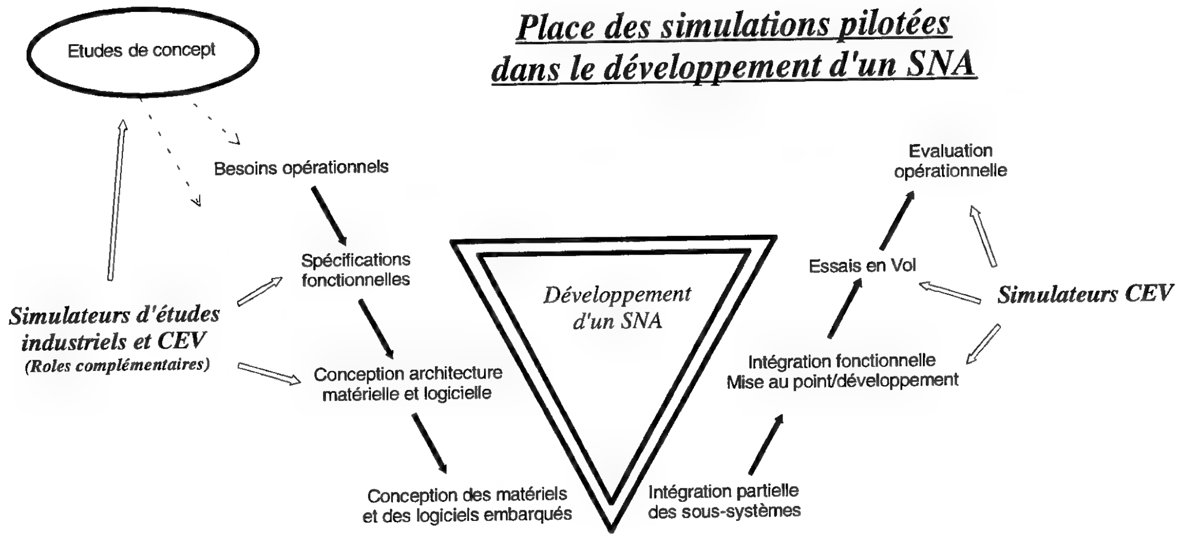

Figure 2. Simulations pilotées et développement des systèmes

La cohérence technique et calendaire des travaux de simulation est assurée par la mise en place d'une équipe intégrée "simulateur" réunissant des membres des différents organismes (CEV, *architecte industriel,* coopérants). Elle s'assure de l'adéquation de l'état de simulation aux besoins des différents utilisateurs industriels et étatiques, et permet d'éviter les surcoûts que pourraient entraîner des doubles développements et de garantir une optimisation de l'emploi des moyens de simulation du programme en respectant les calendriers prévus. Un travail important a notamment été fait pour réduire les délais de transfert des logiciels des sites industriels vers les sites étatiques.

Les travaux de définition système nécessitent la consultation par l'*architecte industriel* d'experts étatiques dans le domaine de l'emploi du système dans les phases de réflexion et de définition préliminaire. Le CEV est mandaté pour coordonner ces activités et en faire la synthèse. En particulier il anime le "groupe pilotes" composé de représentants du CEV et des forces, désignés pour participer au développement du SNA Rafale. Si une partie de ces travaux se réalise sur les simulateurs "d'aide à la spécification" de l'*architecte industriel* tels que le CIH, l'exploitation formelle des simulations des états du système est réalisée sur les simulateurs du CEV (présentations et évaluations).

Le processus de construction puis d'exploitation des simulations pilotées est schématisé en Figure 3.

Nous allons le décrire plus précisément dans les paragraphes qui suivent.

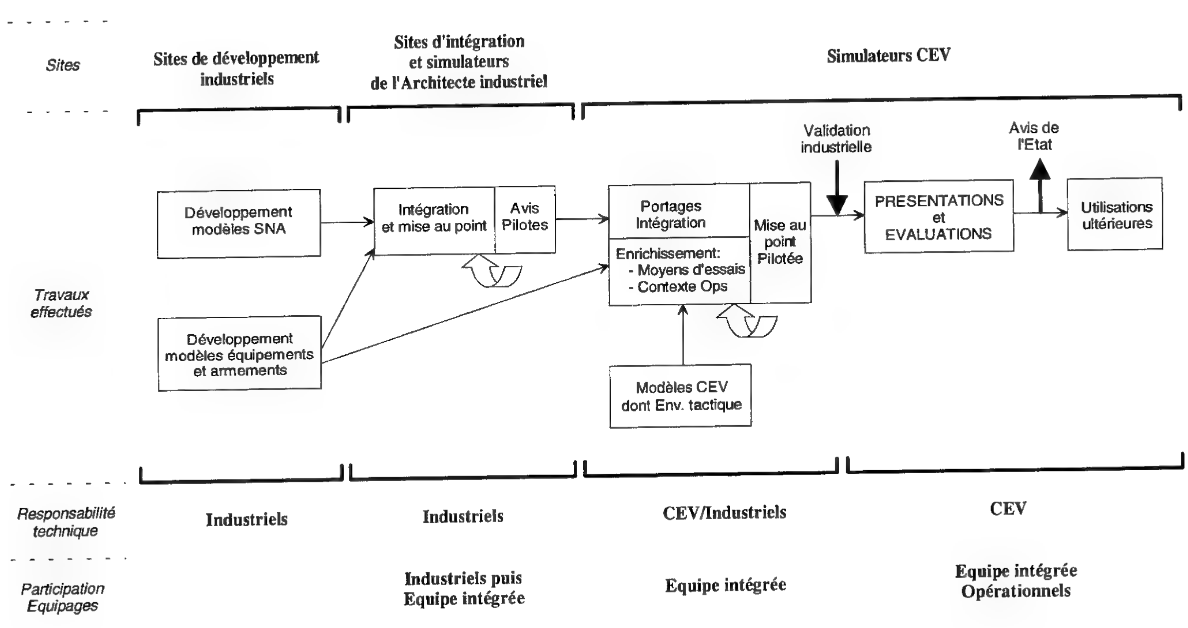

Figure 3. Développement et utilisation des simulations Rafale

4.5 Définition des moyens de simulation

Les choix en matière d'architecture et de moyens de simulations sont guidés par plusieurs considérations :

- compte tenu des rôles respectifs de Dassault Aviation et du CEV et de leur complémentarité, un travail de définition du besoin en simulation est mené en commun. Il est initialisé par Dassault Aviation après identification du contenu des spécifications techniques de besoin et des niveaux de mise au point envisagés; il est discuté et validé par le CEV et complété par l'examen de sa compatibilité avec les moyens d'environnement du CEV (environnement englobant les matériels choisis ainsi que les logiciels de structure d'accueil et certains logiciels applicatifs).
- les moyens de simulation du programme font également l'objet d'une « Vision à Terminaison » technique et budgétaire. Les choix sont guidés par la volonté de respect des principaux standards industriels : Unix, VME, Ethernet, ... de façon à bénéficier des compatibilités ascendantes des matériels et des logiciels nécessaires à la réalisation et à la mise en oeuvre de la simulation pilotée. Ils sont également cohérents des moyens utilisés par les coopérants industriels pour développer et exploiter les modèles qu'ils développent pour cette simulation.

4.5.1 *Architecture*

Le besoin de représentativité de la simulation en termes d'interface homme système et de temps de réponse du système entraîne le besoin de représentativité de l'architecture de la simulation par rapport à celle du système réel. En particulier, le respect du découpage fonctionnel et de l'architecture vidéo est important pour permettre de juger la configuration de la cabine selon la sélection des fonctions et les choix effectués en préparation de mission par le pilote.

Le souci de maîtrise de la faisabilité technique du système (charge de calcul, volume mémoire, débit sur les bus) a également conduit à choisir des moyens sur lesquels la répartition des différents modèles soit représentative des équipements du système réel.

L'hybridation (remplacement de modèles par des équipements réels) étant envisagée, le respect des échanges entre modèles et la conformité aux interfaces des équipements sont recherchés pour faciliter cette évolution ultérieure (voir Figure 4).

4.5.2 *Choix des moyens*

Dans le respect de l'architecture définie, les moyens de simulation sont choisis en fonction essentiellement de deux critères : performances (charge de calcul, volume mémoire et gestion des entrées/sorties) pour les calculateurs et représentativité par rapport aux équipements réels pour la cabine.

Les travaux menés étant de nature différente, les matériels retenus peuvent être différents chez Dassault Aviation et au CEV (Cabine et environnement). En effet, les travaux menés sur les simulateurs CEV nécessitent une très bonne représentativité de la cabine, pour obtenir un jugement pertinent sur l'interface homme système. Dans la mesure du possible, des équipements réels sont utilisés (manche et manette, visualisations, interfaces physiques...) et l'encombrement relatif prévu est strictement respecté. D'autre part, pour restituer des conditions d'emploi opérationnel lors des évaluations, le CEV met en oeuvre des moyens de simulation très importants (visuels et bases de données, sphères de combat, serveur de simulations...). A titre d'exemple les moyens mis en place pour l'étude des conduites de tir multicibles sont décrits dans le texte d'une conférence présentée à l'AGARD en même temps que celle-ci. Ces différences entre les moyens Dassault Aviation et CEV sont identifiées de façon à maîtriser les adaptations nécessaires au

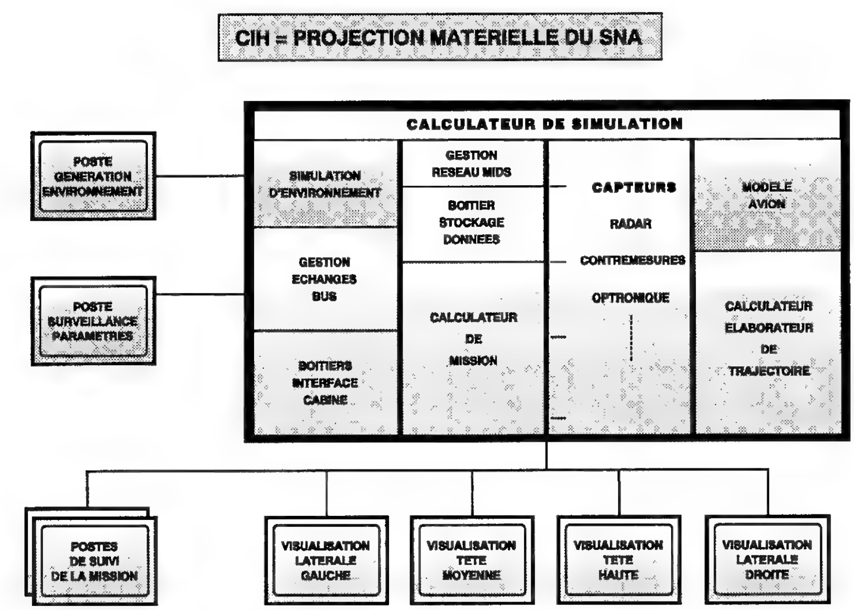

Figure 4. Représentativité de l'architecture de simulation vis-à-vis de celle du SNA

moment des transferts de logiciels (« portages »). Compte tenu de cette démarche et de l'établissement de règles de portabilité, les durées des portages de simulation complète entre Dassault Aviation et le CEV sont faibles.

4.6 Réalisation des modèles

L'architecture de la simulation est définie en tenant compte des fonctions opérationnelles à modéliser et de la représentativité demandée. Celle-ci correspond à la projection de la définition et à son découpage fonctionnel. Deux types de modèles peuvent être distingués : les modèles « capteurs », auxquels il faut associer la modélisation de l'environnement tactique et les modèles du « coeur système » correspondant à la partie du SNA relative aux calculateurs de mission et à l'interface pilote-système.

4.6.1 *Les modèles de capteurs et environnement tactique*

Pour concevoir le système d'armes, la connaissance des capteurs et des armements (classe de performances, caractéristiques, mise en oeuvre) est primordiale car elle conditionne fortement leur utilisation ainsi que la présentation de leurs informations et de la synthèse qui en est présentée à l'équipage. D'autre part, aucun biais ne doit apparaître dans le jugement porté sur l'utilisation du système à cause d'une modélisation erronée ou trop simpliste de ces équipements. Une attention particulière est donc portée sur leur modélisation. Les modèles sont développés par les industriels coopérants responsables de la réalisation des capteurs ou armements réels, à partir des spécifications de besoins établies par Dassault Aviation et le CEV, en fonction des objectifs des essais en simulations pilotées.

Il convient de noter qu'il existe une forte imbrication entre la modélisation de ces éléments et celle de l'environnement tactique (SNA amis ou ennemis, modèles de terrain, environnement atmosphérique, ...). Pour celle-ci le CEV se dote de moyens adaptés aux essais qu'il conduit, qui sont utilisés par les industriels, et servent de référence pour les spécifications de modèles. Les responsables du programme Rafale ont confié au CEV le rôle particulier d'évaluation de la représentativité des modèles par rapport aux spécifications techniques, sachant qu'il a par ailleurs la responsabilité d'approbation du fonctionnement des capteurs de l'avion avant leur intégration au système d'armes de l'avion réel. Dès que cela est possible, le CEV confronte, grâce aux outils et méthodes dont il s'est doté, les résultats des vols d'essais capteurs ou armements sur avions bancs d'essais ou prototypes, afin de recaler les modèles ou d'analyser les dysfonctionnements éventuels. Cela permet d'améliorer en permanence la pertinence des résultats d'essais en simulation.

4.6.2 *Les modèles du coeur système*

Ils sont développés par Dassault Aviation qui a la responsabilité du découpage fonctionnel et du dimensionnement du SNA. Ces modèles doivent être représentatifs et en particulier ceux destinés à simuler les visualisations présentées au pilote qui a besoin de cette représentativité pour mettre au point la définition. Ainsi, dès la conception, un découpage précis et détaillé entre les images et les traitements est réalisé conformément à celui de l'avion. En partenariat avec l'industriel chargé de la réalisation du logiciel embarqué, la définition de ces informations est saisie dans un formalisme informatique adapté à sa réalisation dans les équipements réels. L'outil correspondant permet d'une part la production des spécifications détaillées et d'autre part celle d'un code exécutable sur des générateurs de symboles industriels, ce qui permet de l'utiliser en simulation, que ce soit avec des équipements de visualisation simulés, ou réels dans certains cas (au CEV notamment).

4.6.3 *La modélisation de la préparation/restitution de mission*

Dans le prolongement des différents programmes précédents, mais avec une ampleur renforcée par la polyvalence du système et la superposition des fonctions qui en résulte, la préparation/restitution de mission effectuées au sol joue un rôle très important dans le SNA du Rafale.

Ceci revient à dire que celui-ci possède un segment bord mais aussi un segment sol constitué par la préparation et la restitution de mission, et dont la conception ne peut être menée indépendamment l'un de l'autre. Dans l'attente de disposer du moyen qui sera utilisé dans les forces armées, un système de préparation/restitution des données nécessaires aux essais en simulation est développé comme les autres modèles. Durant la mise au point puis l'évaluation de la définition, il est en effet nécessaire de pouvoir modifier les scénarios d'essais mais aussi la préparation/restitution de mission, pour la rendre cohérente avec le scénario choisi. Il est ainsi possible de montrer aux pilotes les paramètres modifiables soit au sol, soit en vol; ces choix fondamentaux ont en effet des répercussions importantes sur le dimensionnement des ressources du SNA.

4.7 Intégration - mise au point

Les modèles sont développés par les coopérants industriels et par Dassault Aviation, dans le respect des règles de portabilité qui sont un des points clé de la réussite du développement de la simulation. Comme le prévoit le planning général de réalisation de la simulation globale, ces modèles sont ensuite mis en commun au bureau d'études de Dassault Aviation sur l'outil SAMOS (Structure Adaptée à la Modélisation Opérationnelle des Systèmes). Celui-ci est constitué d'un ensemble de stations de travail câblées en réseau et dont la structure d'accueil assure l'intégration des modèles et la mise au point informatique. Cet outil dispose de moyens d'analyse permettant de résoudre les problèmes de cohérence et de complétude de la définition dont la simulation est un bon révélateur. Il peut aussi mettre en oeuvre simultanément plusieurs simulations, ce qui permet de mener les différents travaux en parallèle. Ses limitations sont d'une part un fonctionnement généralement non temps-réel (tous les processus sont appelés de manière séquentielle, mais ils sont exécutés plus lentement) et d'autre part l'absence d'ergonomie puisque les commandes simplifiées sont très différentes de celles utilisées dans l'avion.

Pour s'adapter à l'éloignement géographique entre le bureau d'études de Dassault Aviation et la base d'essais en vol et permettre notamment le développement et la mise au point de l'Interface Homme Système à l'aide de la simulation, une partie de ces travaux est menée à Istres à proximité immédiate des pilotes d'essais, par une équipe spécialisée sur une cabine représentative; il s'agit d'OASIS (Outil d'Aide à la Spécification d'Interfaces Système).

Lorsque la simulation est conforme à la définition, elle est alors transférée au CIH dont l'architecture et les moyens assurent un fonctionnement temps réel de la simulation et sa

mise en oeuvre avec une interface dont l'ergonomie est représentative. Cet outil, comme nous l'avons vu, facilite le travail en commun des différents spécialistes du SNA avec les pilotes (industriels dans un premier temps, puis équipe intégrée Industrie/Etat), pour analyser les difficultés rencontrées et mettre au point la définition par itérations successives, à l'aide de la simulation dans le souci constant de la faisabilité technique.

Enfin, une fois la simulation représentative de la proposition de l'*architecte industriel*, elle est transférée sur les simulateurs du CEV, ou elle est enrichie des moyens de simulation étatiques, et préparée pour une utilisation en contexte opérationnel. L'état de simulation final fait l'objet d'une « validation industrielle », réalisée par Dassault Aviation et les coopérants, ce qui garantit la reconnaissance des résultats obtenus pendant les phases de présentation puis d'évaluation.

4.8 Présentation - évaluation

Deux grandes phases d'utilisation de la simulation pilotée pour chaque état de définition du système devant effectivement être réalisé (étapes intermédiaires et standards utilisateurs) sont prévues :

- les **présentations** officielles par l'Industrie,
- les **évaluations** étatiques.

La **présentation** est le processus au cours duquel l'état de définition du système est présenté à l'Etat par l'*architecte industriel* pour approbation avant réalisation des logiciels embarqués. La simulation pilotée joue le rôle d'une image dynamique des spécifications qui permet aux pilotes étatiques de porter un jugement sur la fourniture, ce qui ne serait pas possible par une simple lecture critique de documents. Cette présentation a normalement lieu sur les simulateurs du CEV (sans délai par rapport aux travaux industriels, grâce au travail technique des équipes intégrées "simulateurs"). Le contrôle de la représentativité de la simulation et la synthèse des avis des représentants de l'Etat sont de la responsabilité du CEV. A la suite de ces travaux, un état accepté des spécifications est élaboré, en concertation avec les différents intervenants.

L'**évaluation** est un processus purement étatique, grâce auquel l'Etat peut porter un jugement approfondi sur la fourniture industrielle (expertise amont pendant la définition et la réalisation du système). Au cours de cette phase, le CEV étudie l'emploi du système dans des conditions les plus proches possibles des missions opérationnelles prévues, parfois avec des données confidentielles vis à vis de certains des industriels. D'autre part, à l'aide des spécialistes du domaine, il analyse les problèmes liés à la charge de travail de l'équipage sur des scénarios d'emploi opérationnels réalistes. Les résultats de ces évaluations peuvent se traduire par:

- une prise en compte des remarques dans des états ultérieurs du système,
- des actions de correction de la définition en cours de réalisation (différents cas contractuels).

Par l'intermédiaire de ces deux phases d'utilisation des simulations, le CEV formalise ainsi vis à vis de l'Industrie une prise en compte des besoins opérationnels dans le domaine de l'emploi du système, le plus tôt possible avant réalisation définitive, mais en fondant les avis sur une image déjà bien avancée du produit final.

4.9 Autres utilisations

Les simulations du CEV utilisées dans les phases de définition du système peuvent évoluer et répondre à d'autres besoins relatifs au programme:

- les **études de concept** ponctuelles liées à des compléments de développement, ou amendements de la définition
- les activités de **soutien aux essais en vol** et d'aide à la qualification

Dans le cas des **études de concept** (confiées à des partenaires industriels), le processus de développement de l'état de simulation, puis d'exploitation des simulations est tout à fait similaire à celui que l'on vient de décrire, la responsabilité des évaluations finales restant du ressort du CEV.

Le besoin d'utilisation des simulations pilotées en complément des vols d'essais a été mis en évidence et analysé par le CEV. Cette analyse découle notamment de l'expérience acquise dans ce domaine sur les programmes précédents (en particulier dans le cadre du développement du Mirage 2000 ou des études générales sur le multicible). Le **soutien aux essais en vol** repose sur la capacité de disposer d'une simulation du SNA conforme à l'état des logiciels embarqués, complétée de moyens d'analyse harmonisés avec les outils d'exploitation des vols d'essais, ce qui permet:

- de préparer efficacement les vols d'essais, pour en diminuer le nombre (entraînement des pilotes, définition des profils ou points d'essais, répétitions, ...),
- d'analyser plus complètement les vols d'essais, notamment par la capacité de "stimulation" (injection dans une simulation de données issues de vols réels), et éventuellement d'étudier des propositions de modifications,
- de proposer une extension du contexte effectivement accessible aux cours des essais en vol en fonction des moyens disponibles ou de l'avancement réel du développement des différents équipements ou armements (aide à la mise au point puis à la qualification).

5. CONCLUSION

A l'issue de cette présentation qui a permis d'exposer la démarche utilisée pour concevoir le SNA du Rafale, notre conclusion est destinée d'une part à établir un bilan global des résultats de cette démarche, et d'autre part à dégager des perspectives d'avenir sur le rôle de la simulation.

En premier lieu, il est important de souligner que le programme Rafale se déroule conformément aux prévisions, ce qui valide les efforts consentis et les innovations adoptées : la définition générale, construite et mise au point grâce à la Vision Avancée Système, répond aux besoins exprimés et le premier standard utilisateur va entrer en service, dans le respect des coûts et des délais. Les travaux en équipe intégrée des équipes d'essais ont permis d'aboutir à des résultats tangibles.

C'est à la fin de 1992 qu'a été présentée la Vision à Terminaison, constituée à partir d'une première définition de l'ensemble des fonctions du SNA Rafale, avec toutes les capacités Air/Air et Air/Surface. Au début de 1994, la simulation du premier standard utilisateur a été présentée puis évaluée et la définition correspondante finalisée et approuvée par l'Etat, permettant ainsi le lancement de sa réalisation.

Il faut également signaler la qualité des résultats techniques obtenus dans les travaux en équipe intégrée pour définir et construire la simulation pilotée. Ceux ci se traduisent notamment par des délais de portage totalement maîtrisés puisqu'à l'heure actuelle, des simulations dont les modèles représentent environ 300000 lignes de code et sont interfacés par un dictionnaire de 10000 variables, sont transférées en une durée inférieure à une semaine. De même, des développements ou des spécifications sont menés en commun pour d'une part bénéficier de l'expérience et des compétences réciproques et d'autre part faciliter les transitions entre les travaux de mise au point et ceux d'évaluation. Enfin, la cohérence et l'homogénéité des moyens de simulations industriels et étatiques sont une réalité. Les différences, tenant compte des rôles respectifs et de la nature des travaux effectués, ont été clairement identifiées et sont prises en compte pour faciliter l'intégration des modèles.

Ces résultats engagent les responsables du programme à poursuivre les travaux avec la même méthodologie pour la suite de la définition du système Rafale.

Mais nous l'avons vu, l'utilisation des simulations pilotées ne s'arrête pas une fois la définition obtenue et approuvée. Les différents standards du SNA Rafale devront être essayés en vol et qualifiés. L'expérience acquise lors des développements des avions de combat précédents a montré tout l'intérêt d'une utilisation intensive des simulations **pilotées** lors des phases d'essais en vol et de qualification des systèmes d'armes aéroportés. C'est ce qui a conduit le CEV à mettre en place et faire évoluer ses moyens de simulation, ainsi qu'à définir les outils et méthodes de travail pour compléter les travaux d'essais en vol et en améliorer l'efficacité.

Les enjeux techniques du programme Rafale (complexité et haut niveau d'intégration du système, polyvalence, innovations techniques pour les équipements...) et la complexité de la tâche de qualification nécessiteront probablement une évolution des techniques employées pour la simulation. En particulier, le recours à une simulation pilotée hybride, c'est à dire intégrant dans des proportions variables des équipements embarqués avec leurs logiciels est envisagé pour répondre aux besoins de la « branche montante » du V méthodologique de développement du système.

En définitive, simulations pilotées et organisation originale des travaux entre l'Industrie et l'Etat concourent de façon essentielle à la réussite du programme Rafale.

ARC SEGMENT ATTITUDE REFERENCE - ASAR

Simulator Application during the Development Process of a
New Attitude Reference Symbology

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1. SUMMARY

Pilots of modern fighter aircraft with high pitch and extremely high roll rates complain about fast moving and twisting pitch ladders on the head-up display (HUD) and the necessity to virtually concentrate their entire attention on the attitude references in order to maintain orientation in space when performing aggressive three-dimensional maneuvers.

For this reason we were considering a more stationary flight attitude symbology to allow for attitude awareness, which requires less attention and concentration. The result was the introduction of the Arc Segment Attitude Reference (ASAR) Symbology.

After a number of alternating simulator trials and flight tests for further development and refinement of the symbology, a final version was agreed and already implemented in experimental programmes.

2. PREFACE

The Key Role of the Development Simulator

In 1987, the ASAR symbology, was demonstrated for the first time to flight test and operational pilots during simulator trials aimed at improving the attitude reference symbology for the Alpha Jet aircraft.

The simulator demonstration triggered German MoD funding and was the kick-off for further development and flight tests. The change requests and recommendations derived from the airborne evaluations were programmed in the HUD computer symbol generator of the simulator, evaluated and prepared for the next flight test portion.

The simulator equipment was continuously improved to meet EF 2000 standards in hardware and software. Therefore rapid implementation of advanced mission phase symbology, including sensor and weapon indications in combination with high maneuvering potential, became available and allowed the extension of the symbology evaluation beyond the capabilities of the Alpha Jet flight test aircraft.

The first ASAR Version presented 1987

A circular arc segment was used as pitch reference and the angle between aircraft symbol and center of the arc as roll reference (Fig. 1).The dimension of the arc is defined by either 180 degrees minus pitch angle (θ) times two ($180° - 2\,\theta$) or flight path angle (γ) ($180° - 2\,\gamma$).

The first ASAR version, presented to pilots, consisted of two concentric arc segments with center and end markings. Fig. 2 shows horizontal flight where a 180° arc is displayed below the aircraft reference symbol. The dimension of the arc segment therefore will decrease with increasing positive angles for Θ or γ or increase with negative angles for θ or γ.

The final ASAR Version in 1994

After 3 simulator trials and 2 flight test evaluations a final version was agreed and specified in 1994. As shown in Fig. 3 additional dots and gaps have been introduced to mark pitch angles of θ (γ) = ± 30 degrees and ± 60 degrees. The dots of the lower segment portion remain displayed for angles above the horizon in order to improve the identification of the semi-circular shape.

A dash mark was introduced at the outside of the segment for better roll reference and a triangular mark at the segment center highlights the direction of the line perpendicular to the earth surface.

3. THE KEY ROLE OF THE SIMULATOR

Close interaction between simulator trials and flight test evaluations were required during the development process of the new attitude symbology.

3.1 The Initial Push

In 1987 simulator trials for improving the Alpha Jet HUD symbology were performed in the Dornier Simulator. As an add-on demonstration we offered the segment attitude reference, and the pilots who were very skeptical and reserved

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during the static demonstration ...."leave us alone with new gimmicks"... changed their opinion totally after a few minutes of dynamic maneuvering in the simulator.

"This is a promising symbology; we want to see it in flight test".

3.2 First Flight Test Evaluation in 1989

The ASAR version as shown in Fig. 2 was programmed for the HUD of a prototype Alpha Jet assigned to the German Armed Forces Flight Test Center.

60 flights with 16 flight test and GAF pilots involved were performed with this symbology. The outcome of this assessment was positive, with a number of recommendations and change requests to be incorporated, tested and agreed in the simulator prior to the next flight tests.

3.3 Second Simulator Trials in 1990

All change requests and recommendations which arose during flight test were integrated as far as possible. The simulator trial was conducted with 3 flight test and 6 GAF pilots involved.

There was unanimous agreement that the symbology was superior for air-to-air (A/A) combat, coarse maneuvering and unusual attitude recovery (UAR) but needed further flight testing and possibly refinement for low level navigation, air-to-ground (A/G) and instrument flight applications. There were also some reservations concerning HUD clutter with ASAR and mission symbology combinations.

3.4 Second Flight Test Evaluation in 1991/1992

The basic symbology which was developed during the second simulator trials was also flight tested with an Alpha Jet aircraft with 40 flights and 13 pilots involved (5 flight test and 8 GAF). The final report was available in early 1993. Again, the common opinion was: The symbology is better than the pitch ladder for A/A, UAR and attitude awareness with some reservations concerning low dynamic flights and HUD clutter as soon as complete mission phase symbology is added to the ASAR. The latter was already commented during the preceding simulator trials.

At that point we reached the limits of the Alpha Jet as test aircraft. Because of the HUD with limited field-of-view (FOV) and the lack of airborne radar, advanced sensor and weapon symbology could not be generated.

3.5 Third Simulator Trials in 1994

At this time we had our EF 2000 research cockpit and aircraft software available to simulate the symbology in a highly dynamic environment.

We prepared computer models for:

- maneuvering targets
- Radar A/A combat modes
- A/A weapon envelopes
- Approach and landing guidance
- A/G LOFT maneuvers

and combined the EF 2000 mission phase symbology with the ASAR. The pilots were able to switch without interruptions or delay between pitch ladder (PL) and ASAR symbology including the mission phase symbols during maneuvers in any mission phase.

For mission phases which do not require dynamic maneuvering but precise pitch references a simplified PL was added to the ASAR as primary mode.

12 pilots were involved in this simulator trial (8 test pilots + 4 operational pilots).

The test pilots refused to apply rating scales, like Cooper-Harper or modifications thereof, stating that the tasks were too complex with too many parameters involved, so that standard ratings scales could not be applied. We ended up with around 40 pages of written comments.

Task set-up for this simulator trial

- Evaluation of the latest changes to ASAR
- Evaluation of Unusual Attitude Recovery (UAR)
- Evaluation of A/A-symbology in combination with PL or ASAR
- Evaluation of A/G-symbology (LOFT maneuvers) in combination with PL or ASAR
- Evaluation of basic flying phase symbology in combination with PL or ASAR + PL for Approach, Landing, Take-off and IFR-Navigation.

Simulation Results

- Basic ASAR symbology as demonstrated was accepted and frozen.
- Unusual Attitude Recoveries were accomplished faster with ASAR, up to 30 % for pilots with previous ASAR experience
- A/A symbology with ASAR was rated superior to the PL, even pilots who were skeptical before changed their mind
- A/G symbology with ASAR better or equivalent to PL
- Basic instrument flying symbology better or equivalent to ASAR + PL compared to PL only.

Overall opinion of the pilots was that the ASAR symbology was better than PL for all mission phases for HUD and helmet mounted display (HMD) applications.

4. PRESENT ASAR APPLICATIONS IN R & D PROGRAMMES

4.1 X-31 Research Aircraft

The ASAR and the THETA-symbology is used on the X-31 HUD for attitude reference.

The THETA symbology is a three-dimensional globe-type display with the aircraft symbol in the center.

The test pilots of this programme favour the THETA display, but this aircraft has no mission phase symbology which, most probably, would totally clutter the THETA display.

4.2 Tornado Helmet Mounted FLIR Display

In this German MoD funded research programme the ASAR symbology is used for attitude reference in the HMD in combination with the FLIR picture.

According to the draft of the final report the test pilots are happy and feel comfortable with this flight attitude reference.

5. FURTHER PLANNING

The next simulator trial is planned for June/July 1995 after the latest EF symbology changes have been programmed. Presentation to EF 4 nations Cockpit Assessment Working Groups pilots is planned by end of the year with a HMD integrated into the simulator cockpit. On this occasion we also intend to integrate angle-of-attack reference with the ASAR using a variable aircraft symbol.

Fig. 1 Arc Segment Attitude Reference - ASAR Explanation

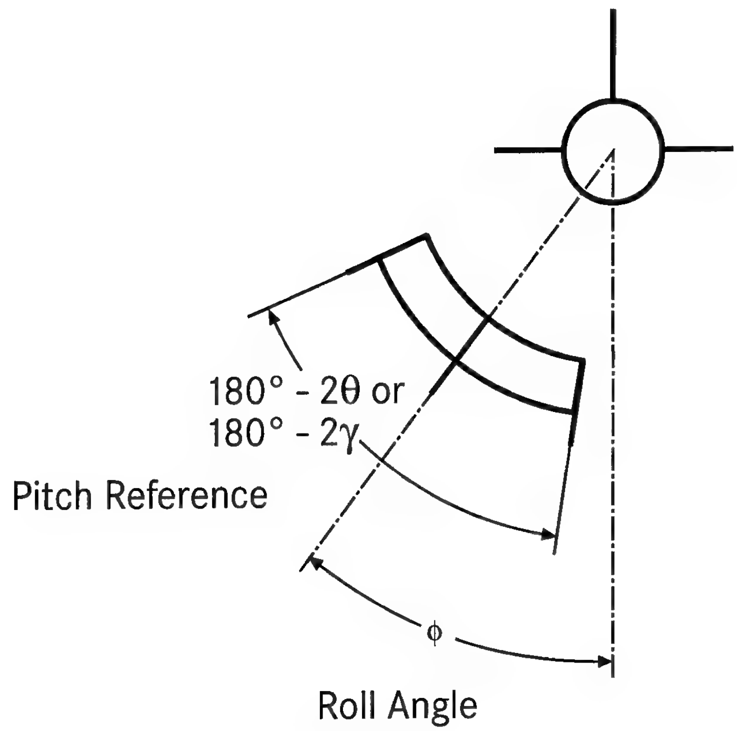


Fig. 2 First ASAR Version -"The Orange Peel"

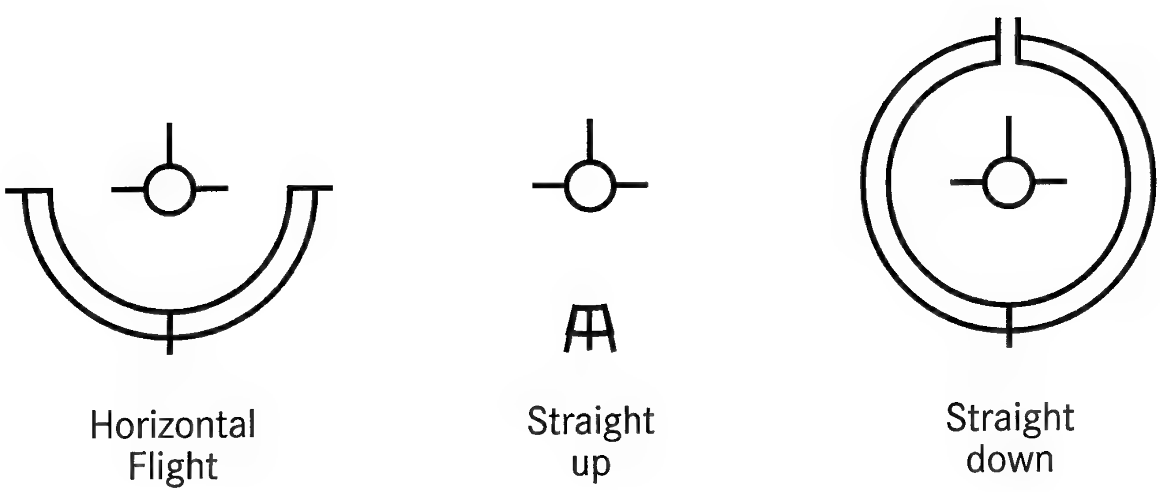
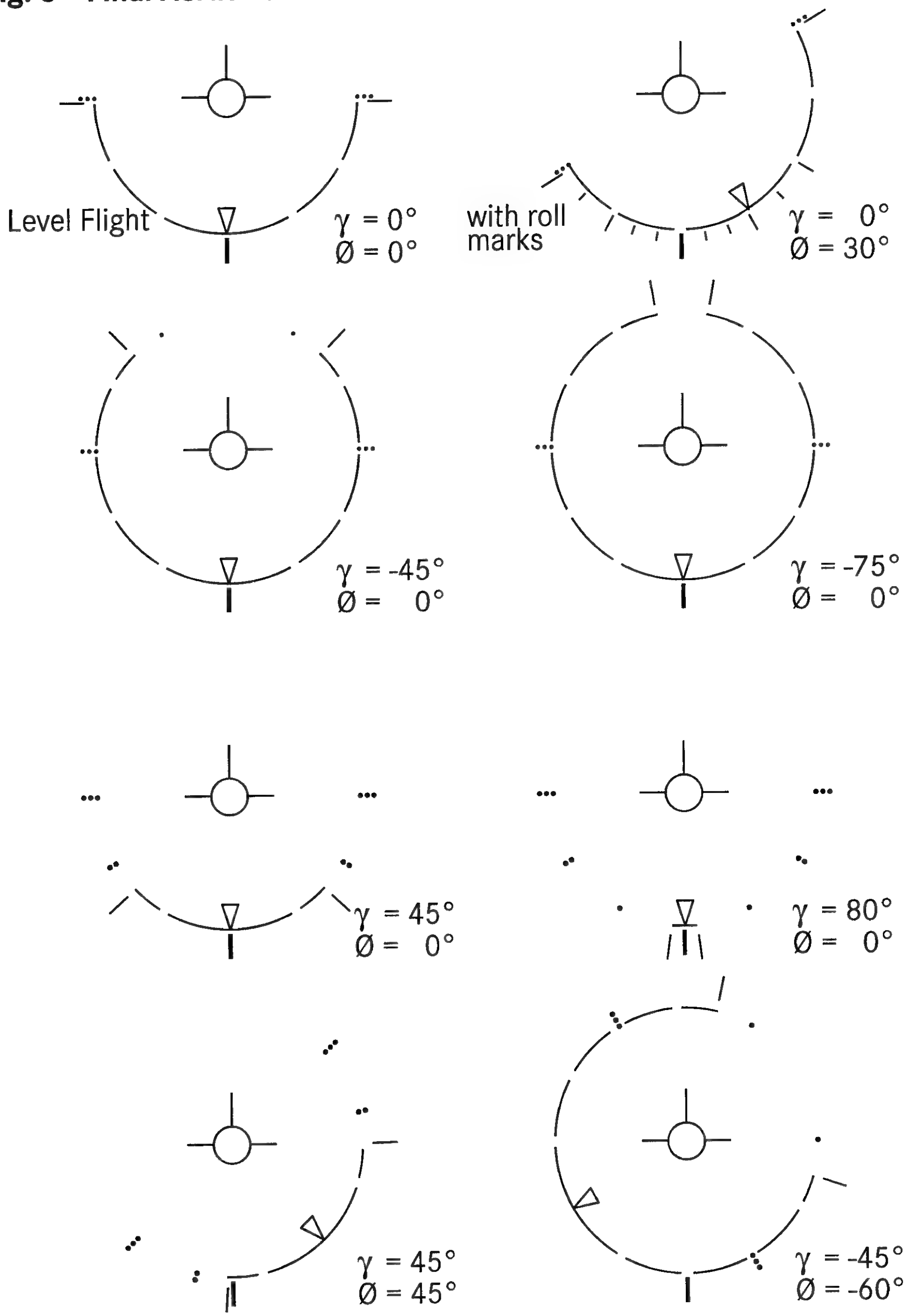


Fig. 3 Final ASAR Version



Issues in the Flight Clearance of Vehicle Management Systems

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Summary

The adoption of highly-integrated and complex aircraft systems will facilitate the development of optimum strategies for vehicle management. This will provide benefits in functional performance and operational effectiveness. The drive towards standardisation implies the adoption of some form of modular avionic architecture, thereby adding the benefits of improved logistics. In this paper, it is argued that these developments force a fundamental review of existing approaches to flight clearance. A number of challenges are proposed in the areas of Operating Systems, Analytical Control Theory and 'Virtual Rig' Simulation. In conclusion, the paper anticipates the evolution of a "modular" procedure which might provide a legal basis for the certification of aircraft systems.

1 Introduction

Vehicle Management System (VMS) concepts are accepted as the basis for improving the performance of future aircraft. Traditional airborne systems satisfy objectives which have been specified within narrow functional boundaries. The new opportunity is to apply software control in order to coordinate and optimise dynamic interaction and transient response across all aircraft systems. In this way, new system objectives can be pursued. For instance, energy efficiency can become a design driver whereas, hitherto, this particular property was unmeasured and uncontrolled.

The scope of VMS functionality creates the dual problem of complexity and diversity. Increased connectivity enables functions to exploit shared data but the open nature of the architecture removes many of the traditional defences against comprehensive fault propagation. Attempting to integrate diverse functions introduces a range of interfacing problems. Also, it becomes very difficult to establish the most appropriate optimisation policy in the face of large-scale system models.

An emerging factor for VMS implementation is the drive towards standardisation. This will lead inevitably to the adoption of some form of *Advanced Avionic Architecture* (A3) although safety considerations will rule out the use of fully reconfigurable, fault tolerant computing. This aims to achieve cost reduction through the provision of standardised modules, housed in modular racks and connected by a communication network. Feasibility studies have been conducted under the Allied Standard Avionics Architecture Council (ASAAC) and elsewhere, but a large amount of new work is required to how generic resources can be managed by a distributed operating system **and** be used for safety-critical applications.

The principal benefits of VMS integration lie in four main objectives:

- **rational grouping of system functions**
- **unified approach to system implementation**
- **flexible allocation of system resources**
- **scalable architecture which supports expansion**

The main challenge concerns the safety case and, therefore, the flight clearance of a software-controlled system which is complex and highly integrated.

This paper will consider the principal issues in the flight clearance of a VMS. It will be argued that clearance depends upon properties of determinism, robustness and testability. This is influencing the research agenda in a number of key areas, *especially* A3 operating systems, analytical control theory and 'virtual rig' simulation.

2 Concept of Vehicle Management

An essential feature of VMS philosophy is to provide an integrated control system which flies an *Aircraft* and provides management of *Stores* (*i.e.* weapons, external fuel tanks and so on) and *Energy* (*i.e.* fuel, power, cooling and so on). Overall objectives include:

- **'carefree handling' (*including* high-*g*, high-α, severe turbulence and engine surge)**
- **reduced pilot workload *via* vehicle automation**
- **rapid response and precision flying tasks (*especially* weapon delivery)**
- **efficient airframe resource management**
- **environmental protection of installed equipment**

This demands a unified approach to functional specification and design which can be applied to all airborne functions. It will require a comprehensive method for analysing system requirements and for assigning functions to appropriate implementation methods. A **high** level of functional integration is assumed and, accordingly, the behaviour of each part of the system will be dependent upon correct behaviour of other parts of the system.

2.1 System Attributes

In the most general context, an airborne *System* provides the host aircraft and its users with an operational capability within a prescribed environment. The limits of that capability are defined by an *Operational Envelope* which is appropriate to the current system configuration. This is a parametric description of all reachable states of a system (*e.g.* position, velocity, temperature) and all constraints imposed by its environment (*e.g.* structural strength, control power) or its user (*e.g.* *g*-onset leading to sudden loss of consciousness). Note that the concept of reachability has meaning if and only if the system is predictable and controllable.

The organisation and interconnection of system elements is called an *Architecture*. The type of element depends upon the type of design activity being conducted at a particular stage of development and the type of partitioning which is being applied to the system. Early in the development cycle, the type of element is a function; during implementation, it will be a item

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of hardware or software. The hardware elements which make up the system infrastructure, together with their management software, are called *Resources*.

The behaviour of a system element has five basic attributes, as follows:

Operation The way in which the system element is used to support the system operation.

Task What the system element does when it is activated, as described by a constitutive relationship and an interface specification.

Performance Speed and accuracy of response of the system element when it is activated, expressed as combinations of ***value*** and ***time***.

Resource The dependency of operation, task and performance on system resources.

Failure The effect of loss of system resources on the system element and the way in which such a loss can occur.

This provides a complete operational definition, which can be applied to system elements (either individually or collectively) at any level of architectural decomposition.

Applying these attributes at system level, the following characterisations can be defined:

System Type	Attributes	Requirement
Real-time System	Performance	Deadline Timing
Control System	Operation Task Performance	Continuous Modify Environment Periodic Deadline Timing *plus* Frequency Response

A *Real-time System* has timing constraints imposed such that the system functions deliver a service within a known time interval after they have been activated. Note that 'real-time' does not necessarily mean 'high performance'. A *Control System* is any real-time system which modifies the dynamic behaviour of its environment. This is achieved by means of applied power which is continuously modulated as a result of operating commands and physical measurements.

2.2 System Abstraction

System design can be interpreted as a hierarchical abstraction, as follows:

Functional Architecture	
Process Architecture	
Hardware Architecture	Software Architecture

The intention is to impose a structure on the information needed in order to develop a system concept into a system product. The hierarchy contains a mapping between different architectural definitions. Operational requirements are applied at the top: implementation constraints are applied at the bottom. Within the hierarchy, system requirements are passed top-down and system constraints are passed bottom-up.

The behavioural model of a system is defined by the *Functional Architecture*. The overall structure of resource utilisation, both to satisfy functional requirements and to provide operational integrity under failure conditions, is represented by the *Process Architecture*. This is the computational model which will dictate how the system is to be built. Conceptually, processes are the units of execution for system functions and these will implemented as items of hardware and software. The eventual implementation will comprise the *Software Architecture* and will produce so-called applications from software modules (standard services and specialised code). The structure of system resources is defined by the *Hardware Architecture*. Note that the user interfaces for the system are defined at the level of functional architecture and then mapped on to lower levels.

The traditional model of system implementation is based upon a federated architecture of Line Replaceable Items (LRIs). Each has its own dedicated resources and can operate independently; integration is performed at the functional level and is facilitated by a communication network. A simple structure can be identified, as follows:

DEVICES	APPLICATION
	Line Replaceable Item
NETWORK	

A partition is applied down to the network level, according to whether functions are to be implemented using devices (*i.e.* sensors, actuators, controls and displays) or applications (*i.e.* software items). In this model the application software controls virtually all aspects of hardware (LRI) utilisation. The process architecture furnishes an LRI Processing Specification which dictates the software construction for particular target hardware.

The implementation model for an A3-based system is interpreted as a more elaborate structure, as follows:

	APPLICATION
	APOS Interface
DEVICES	OPERATING SYSTEM
	MOS Interface
	MODULE
NETWORK	

The rationale for this type of layered abstraction is the need for hardware transparency at the application level. This will support (in principle) the use of different modules, perhaps incorporating new technology, without the need for software re-engineering. The same partition is applied between devices and applications, but the application mapping is structured by two interface layers, which enforce standardisation.

The purpose of each layer of the implementation model is described, as follows:

- **DEVICE** layer contains functional mechanisms which embody mainly the analogue process definition of the system and the interface between analogue and digital processes.
- **APPLICATION** layer contains executable software which embodies most of the digital process definition of the system.
- **APOS Interface** layer provides a virtual machine interface for "application to operating system" (or APOS) mapping.
- **OPERATING SYSTEM** layer contains a set of services which manage the process execution defined in the application layer. The operating system 'owns' all system resources and all system time.

- **MOS Interface** layer provides a transparent interface for "module to operating system" (or MOS) mapping.
- **MODULE** layer contains processor and memory resources and provides a physical interface to the network.
- **NETWORK** layer contains physical resources for data communication.

The particular value of this model is to convey a generalised concept of system resources - partly hardware and partly software. Thus, the **MOS** will specify standard hardware resources and the **APOS** will specify standard software resources. In the process architecture, both types of resource are available and the aim is to maximise their usage in order to minimise the amount of application-specific software to be developed for any given system. For instance, where hardware redundancy management is required, it is possible that the voter-monitor algorithms (which are currently treated as part of the **Application**) will be incorporated as standard services within the **Operating System**.

2.3 VMS Implementation Requirements

The perceived benefits of systems integration are two-fold, namely improved functionality (performance, fuel economy, etc) and improved logistics (reliability, availability and maintainability). This can be exploited in order to reduce design margins (either to increase performance or to reduce cost) but, as a result, the system safety assessment will be complicated. The critical trade-off for the customer will be cost-effectiveness, that is 'cost of ownership' *versus* 'operational effectiveness' at **acceptable** risk.

Achieving these benefits is the responsibility of the system designer. Typically, the design is conceived middle-out rather than top-down. This allows due weight to be given to existing engineering knowledge without being forced to use a "clean sheet of paper" every time. It also provides flexibility in reconciling technology selection, customer requirements and commercial constraints.

At early stages of development, a system implementation has not yet been built and experience with real hardware and software is generally lacking. This is especially true for A3-based proposals because even the hardware, software and system management concepts have not been fully defined. Also, as system complexity increases, the implementation issues become much more difficult to grasp. For VMS integration, the building blocks are quite large, complex subsystems in their own right, *e.g.* propulsion, flight control, secondary power and environmental conditioning. Functional integration serves to bind these subsystems together in a manner which hitherto was not possible. This in turn opens up new opportunities for equipment design because a suite of equipment can be configured *ab initio* with integration in mind and this becomes an objective in the design optimisation. This is particularly true in the area of engine thrust/power offtake, where new packaging concepts are being developed for power generation.

All of these factors point to considerable uncertainty in design and implementation of a future VMS. There is a dual problem of complexity and diversity; the existing problem of handling complex designs is likely to be more severe and be compounded by new integration concepts which encompass a much greater range of functionality than hitherto. This demands tools which are capable of simulation of large-scale diverse systems, at any level of abstraction. It also demands a development methodology which is modular and can be applied at different levels of product definition. This would support re-use of system components and a phased clearance of new system configurations, starting with simulation and progressing towards full implementation.

At every stage of development, a modular approach is required which can handle all issues of functional complexity at a detailed level of design and concentrate on integration issues at an aggregate level. This leads to a dual interpretation, namely [i] a set of interacting system elements or [ii] a network of flowing information. A modular approach to system **design** is possible by decomposing the overall specification into individual specifications for elements of the system architecture. A modular approach to system **qualification** is then possible such that each system element is shown to satisfy its own specification and the network connections provide a traceable link between systems elements. The definition of system architecture depends upon the level of abstraction that is appropriate to the stage of system development. What is important is that traceable links can be demonstrated between different levels of abstraction and that, within each level, compatibility can be demonstrated.

Equipment standardisation and cost reduction are well-established as system design drivers. The logistic gains which may be achieved from A3 are large, provided that safety issues can be resolved. It is clear that benefits can be realised by adopting a common architecture for VMS functions which can support the availability requirements for safety-critical applications. The argument rests on pragmatism such that a common module type could be specified with a level of hardware isolation suitable for all critical control systems (with a compatible segregation policy for the backplane). This is less ambitious than applying fault tolerant computing techniques and it will relax the operating system requirements. In this way, functional isolation can be supported by physical isolation where necessary, without stipulating logical or temporal isolation. The real requirement is for safe and secure isolation without excessive development cost or timescales.

The most pressing priorities for A3 management concern the scheduling and allocation of system resources. For VMS implementation, the principal aims are to achieve hard deadlines for software execution, distributed resource management and deterministic operation. The deadline policy must be **hard real-time** in order to satisfy the performance and safety requirements associated with the external environment of the system, *especially* the avoidance of hazardous events. Distribution is a requirement which might be derived from system architecture, software size or functional isolation. It is likely that the allocation of resources will be predominantly static and redundant, with some level of dynamic switching (*e.g.* to isolate resource failures). Note that the need to share data between resources creates an 'internal' requirement for hard deadlines on processing and communication because, otherwise, it would be impossible to satisfy 'external' hard deadlines. In all of these respects, operating system research will be critical.

In summary, the benefits of increased efficiency and decreased logistic support are central to VMS concepts. The challenge is to actually achieve these benefits within cost and safety limits.

2.4 MMI Requirements

There are important questions which must be raised in connection with the *Man-Machine Interface* (MMI) requirements for VMS. These concern the control/display modes which

support, firstly, an appropriate level of automation for particular functions and, secondly, the actual level of influence which can be exercised over particular functions.

Piloted simulation is an essential aspect of system clearance, particularly in the areas of flight control and cockpit instruments. The rationale for building expensive facilities and for supporting research into *Virtual Reality* is that a human operator will exercise a system simulation in a representative and exhaustive manner if the psychological cues are believable. Human factors are of importance, not only because the pilot is the ultimate end-user of an aircraft but also because subjective assessment by an independent expert (*i.e.* a test pilot) gives invaluable insight into the adequacy of system design. Rating schemes exist for aspects such as handling qualities (*cf.* Cooper-Harper ratings) and these serve as the basis for comparing and contrasting different human reactions, thereby accommodating the type of variability that would be encountered in service. In addition, an independent expert can play "devil's advocate" and, as such, prompt further development of a system.

The new challenge which arises in a complex and highly-integrated system is the method of exercising system functions in a way which has proved so successful for, say, flight control systems. Much of the VMS functionality will be automated and the behavioural characteristics will depend upon interfaces with other functions. How then can effective simulation experiments be designed? The scientific imperatives are not clear in this area and research is urgently required.

By analogy with existing practices in flight simulation, the obvious first step is to attempt to emulate human characteristics in determining simulation objectives, some of which are highly structured, some are random and some are context-dependent (*e.g.* workload). In other words, a pilot is partly ruled-based, partly fuzzy and partly chaotic! Training will encourage structured behaviour but chaos might still occur under conditions of high stress or uncertain information. As far as is known, this mix of imperfect human qualities gives high coverage of potential problem areas and is a proven technique for finding snags.

The challenge to simulation specialists will be to recreate this level of confidence for complex systems which do not rely upon human action or intervention. An overview of possible control/display modes is instructive:

Control Modes	**Characteristics**
Manual	Full manual operation
Protected	Carefree manual operation *via* monitoring
Augmented	Assisted manual operation (high performance)
Selected	Pre-programmed automation
Pre-selected	Adaptable automation
Automatic	Full automation (autonomous operation)
Display Modes	**Characteristics**
Continuous	Essential data
Cooperative	Informational data to assist manual operation
Interactive	Generated data in response to manual operation
Selectable	Non-essential data
Advisory	Event-driven data
Diagnostic	Fault-finding data

These represent a large number of system design options and depend heavily on the concept of optimality being employed. All of these modes are different and, more importantly, all of these modes will be present in future aircraft (plus a few more, no doubt). Perhaps what is really needed is a new breed of super-human test pilot. **Figure 1** suggests a possible long-term option although there is some concern regarding high-***g*** manoeuvres!

Serious questions must be asked when assessing current practice against future VMS requirements. Integration will yield more combinations of functions than can be tested and much of the functionality will be transparent to the user and, therefore, also transparent to a test pilot who is flying a simulator. Thus, a new approach will be required for automated test procedures, which can identify what test coverage has been achieved and furnish objective evidence that the coverage is sufficient to address safety requirements.

3 Concept of VMS Simulation

Vehicle management involves a wide range of airborne functions, integrated in an optimum manner. What is readily apparent is that extensive simulation will be essential in order to furnish a proof of concept which will justify the large investment required for development. Effectively, simulation must support a preliminary "design clearance" and, accordingly, the scope and depth of simulation must be such that detailed analysis of VMS behaviour is possible.

This section will introduce and describe briefly seven complementary but different viewpoints on VMS structure. The aim is to demonstrate not only the complexity of the system but also the number of overlapping interpretations which exist. Each relates to a different type of behaviour and, thus, a different type of simulation model.

Aircraft Viewpoint

A simple block diagram is a good starting point for introducing more detailed descriptions of a VMS. In **figure 2** an aircraft platform is shown schematically, carrying weapons and containing a system (the VMS) and a cockpit. The cockpit supports the aircrew and provides them with controls and displays (designated 'C' and 'D', respectively) which allow them to interact with the system. The system interacts with the aircraft (because it is controlling the aircraft!) and the aircraft interacts with the outside world environment (airmass, terrain and so on). Finally, the outside world provides visual cues for the aircrew; motion cues are acquired directly through the aircraft.

Physical Viewpoint

For illustration of the physical integration of the aircraft and its embedded equipment, a schematic is presented in **figure 3**. The *Aircraft* is described in terms of its longitudinal aerodynamics and its major airframe 'components', namely *Engine, Fuel, Cockpit* and a set of other enclosures which, for convenience, will be called *Zones*. The intention is to indicate the principal sources of interaction between the aircraft and its embedded systems and, to this end, the schematic should be self-explanatory. Attention is drawn to the so-called *Integrated Power Offtake System* (IPOS), which is a merely a packaging concept covering a range of airbleed and power offtake requirements.

__Equipment Viewpoint__
A more uniform structure is shown in **figure 4**, which concentrates on the functional partitioning of equipment within the airframe. It also shows the interactions between system, cockpit, aircraft and outside world, as contained in the *Aircraft Viewpoint.* Interfacing takes the form of Controls (C), Displays (D), Actuators (A), Sensors (S), Inputs (I) and Outputs (O). It is assumed that the so-called *Zones* will contain the system processing resources.

Functionality has been added for primary actuators (which are essential for aircraft flight), secondary actuators (for ground handling and optimised flight) and aircraft sensors (as distinct from system sensors).

__Communication Viewpoint__
The passage of information around the system is handled by a data network, as shown in **figure 5**. Note that a digital process is characterised by information transfer whereas an analogue process is characterised by energy transfer. This provides all the interfacing that was identified in the *Equipment Viewpoint*, with the exception of actuators and sensors which are local to the equipment zones.

__Functional Viewpoint__
Figure 6 shows the arrangement of 'control' and 'manager' functions which provide the inner-loop connections around the airframe equipment. The distinction is based on stereotypes. Control functions are considered to be high-performance and non-optimising: manager functions are low-performance and optimising.

The underlying philosophy should be self-evident although it is worth noting that Flight Control and Airframe Control are not shown as independent functions. This reflects the current debate regarding the layout of future aircraft platform sensors. For convenience, it is assumed that **__all__** sensor information will be coordinated through a Sensor Manager.

__Processing Viewpoint__
The 'control' and 'manager' functions, identified in the *Functional Viewpoint* will be physically incorporated within an equipment zone, *e.g.* an A3 modular rack. **Figure 7** attempts to show the general form of partitioning that is envisaged although **__no__** attempt is made to allocate particular functions to particular modules. The intention is to indicate that, somewhere in the *Zone*, there resides a Flight Control function (say) which is served by a local data network and a local power network.

Zone-specific features are highlighted, namely the Interface Module, Power Supply Module and Zone Manager. Essentially the Zone Manager is responsible for all aspects of energy and resource management within its zone, such that it handles cooling, power distribution and computing hardware at local level. The rôle of sensors and actuators is seen here as an environmental task, without loss of generalisation. The important point to note is that measurement and control of the zone environment are handled locally *via* the Interface Module and the Zone Manager.

__Integration Viewpoint__
Figure 8 offers a broad overview of system functionality **__and__**, most importantly, an interpretation of functional integration. It shows a composite of *Aircraft Viewpoint* and *Functional Viewpoint*, with an exploded view of the VMS **__plus__** additional functionality which supports a mission capability.

4 Concept of Flight Clearance

Flight Clearance is the process of validation and verification which demonstrates that an aircraft is safe to fly. It must ensure an appropriate level of dependability for the aircraft and its embedded systems. It must be based upon a set of design concepts, implementation standards and operating procedures which minimises or removes the risk of accidents.

4.1 Dependability

There are various interpretations of the term *Dependability* although all convey the general consensus that a system is fit for purpose. The particular interpretation adopted here is based upon those concepts which are critical to flight clearance. A summary is given below.

- *Certification*
  Legal recognition that a system complies with statutory requirements, *e.g.* airworthiness regulations and health and safety legislation.
- *Qualification*
  Documentary evidence that a system will operate safely in accordance with its specification and that adequate procedures were imposed during development in order to provide proof of design.
- *Safety*
  Confidence that a system will behave in accordance with its specification without causing harmful effects.
- *Survivability*
  Ability of a system to continue operating within a specified hostile environment, as defined by the notions of susceptibility (*i.e.* the probability that a fault may be induced by a defined threat) and vulnerability (*i.e.* inability to tolerate damage resulting from an encounter with a threat).
- *Robustness*
  Ability of a system to accommodate failure effects or changes in the system environment, thereby providing a margin of protection against unplanned events which would otherwise have unpredictable and possibly catastrophic consequences.
- *Predictability*
  Stipulation that a system will behave in a known manner within its prescribed operational envelope.
- *Testability*
  Ability to perform operational checks on a system.
- *Availability*
  Time/resource constraints within which a system can provide its intended operational capability.

4.2 Fault Propagation Model

For current purposes, a *Fault* in a system element is defined to be any **__unintended__** change in its behaviour (*i.e.* outside normal operating tolerances). A *Failure* is an **__extreme__** change in behaviour such that, for all practical purposes, the system element is no longer operational. The relationship between the two is shown in **figure 9**, together with a perspective on possible fault mechanisms.

System properties can be affected by component defects (*e.g.* a manufacturing flaw or a degradation in material performance) or by environmental threats (*e.g.* electromagnetic interference). Both phenomena can result from inadequate design, arising either from poor component quality or insufficient protection. However, assuming competent design, the main problems concern components failing with age or an excessive threat impinging on the system. A component defect might render the system vulnerable to a threat or, alternatively, a threat might result in component damage. If defects become significant, either in severity or quantity, they will eventually constitute a fault; if threats cause large disturbances in the system environment, they too will eventually constitute a fault.

Particular difficulties arise when a system element can proceed from a fault condition to a failure condition with no evidence that the fault has occurred. This is called a *Dormant Failure* because it is hidden until the system element becomes critical. The issue of dormancy is not easy to solve and ultimately must be addressed in the system design, taking due care in analysing failure probabilities.

The concept of a system *Error* relates to the capacity of the system to associate behavioural anomalies with known fault mechanisms and to raise an alarm. Assuming that the fault can lead to a failure, the system must initiate **protective** action in order to reduce or remove the failure effects. If the fault corresponds directly to a failure, then **corrective** action is required in order to recover from the failure effects. There appears to be no universal agreement on terminology in this area but it is clear that 'protection' involves *Fault Masking* and that 'correction' involves *Fault Tolerance*. A more basic form of intervention in a system is performed at module level and comprises a set of operational checks which are designed to detect and locate component defects. This is generally called *Built-In Test* and is intended to prevent defects from becoming faults.

4.3 Hazard Identification

A *Hazard* is a condition which is identified as having the potential to cause harm to the aircraft, its occupants and its environment. Obviously, this does not include planned weapon delivery! Typical hazards include

- Loss of structural integrity
- High energy uncontained explosion
- Uncontained debris
- Fires
- Escape of gases or liquids
  (*especially* if hot and/or pressurised)
- Inadequate protection against environmental threats
- Controlled flight into terrain

The hazard risk assessment is based on [i] the worst possible (and credible) consequence of a hazardous event and [ii] the likelihood of a failure which would cause a hazardous event to occur.

Analytical methods are used to identify the hazards which are linked with run-time faults and failures. The principal categories of analysis are, as follows:

- **Failure Modes, Effects and Criticality Analysis** is used to assess the cause and effect (including limits) of all possible failure modes, together with estimates of the probability and criticality of occurrence.
- **Fault Tree Analysis** is performed on a system, in the context of its environment and operation, in order to find all credible ways in which a predefined hazardous event can occur. Note that a fault tree is not in itself a quantitative model, nor is it a model of all possible causes of system failure.
- **Zonal Analysis** is performed a system in order to establish [i] the effects of adjacent failures within a bounded area of the aircraft, [ii] design installation and regulations and [iii] maintenance and operating aspects (including human factors).
- **Energy Trace Analysis** identifies circumstances in which an energy source transfers unwanted energy to a vulnerable target in the absence of adequate barriers.

Hazard tracking is performed so that all risks to the system are reported and the status of risk reduction activities is clearly visible.

4.4 System Integrity

A *High Integrity System* is one for which incorrect behaviour would be unacceptable. The requires a high level of confidence that the system implementation is correct and, thus, that system behaviour is **predictable**. An appropriate methodology will minimise the likelihood of design deficiencies arising from human errors and computer-aided tools by eliminating the circumstances which permit such errors to occur and go undetected. These requirements are expressed by a set of criteria for *Design Integrity*, as follows:

Design Integrity	Attributes	Requirement
High[1]	Operation Task Performance Resource	Predictable Predictable Predictable Predictable
Medium[1]	Operation Task Performance Resource	Short time at risk[3] Predictable Predictable Dissimilar[4]
Low[2]	-	*No specific requirement*

[1] Incorrect behaviour is unacceptable
[2] Incorrect behaviour is acceptable provided it is contained
[3] Mitigates the overall risk if and only if the time at risk is short
[4] Substantially reduces the probability of incorrect behaviour

In addition to design deficiencies, it is recognised that incorrect behaviour can arise during system operation due to failures. Thus, a high integrity system must embody a set of design concepts, implementation standards and operating procedures which minimises or removes the risk of unacceptable failure effects. This requires that, firstly, the system failures are **predictable** and, secondly, stability and performance are **robust** to any change in system characteristics. This requirement is expressed by a set of system-level criteria for *Operational Integrity*, as follows:

Operational Integrity	Attributes	Requirement
Fail Operational[1]	Operation Performance Failure	Continuous/Essential Robust Predictable
Fail Stop[2]	Operation Failure	Selectable/Non-essential Predictable

[1] Failure effects are unacceptable
[2] Continued operation leads to unacceptable effects

Note that a *Safety Critical System* is a special type of high integrity system for which 'unacceptable' means 'hazardous', either resulting directly in an accident or substantially increasing the probability of an accident. In fact, it is common to use the safety analogy when discussing the risks associated with any type of critical system. For this reason, the term "fail safe" is usually preferred to "fail stop".

Using the above criteria, the formal options for safety-critical system implementation are [i] a high or medium level of design integrity and [ii] fail operational or fail safe response (as appropriate). The particular choice of option depends upon the nature of external hazards and upon the requirement for continued operation of the relevant part of the system.

4.5 Flight Clearance

For any system intended to be safety critical it is essential that such a requirement be identified at an early stage of development, preferably at the outset. "Safety" cannot be applied retrospectively without incurring significant penalties, because the level of design integrity has to be increased. As has been demonstrated on numerous occasions, any attempt to do so is generally very expensive, even assuming that it is possible! Contrary to popular belief, if a safety critical methodology is applied from the start, the resulting overhead may not be particularly large. Indeed, as a result of the greater rigour applied to the development process, some costs might actually be reduced because the system is more likely to work first time, thereby removing the need for re-work and re-testing.

Given the scope of functionality involved, it is clear that a VMS is clearly going to be safety critical. Its operation will be essential to aircraft flight and, therefore, it is therefore possible to proceed directly to define both the properties which must be exhibited by any VMS concept and the proof required in support of such a concept. The properties needed are:

Determinism
Robustness
Testability

These must be incorporated at all stages of design (*i.e.* in each definition of system architecture) in order to provide high integrity. Effectively, what is being stipulated is that system behaviour is pre-determined as far as is practicable (under both nominal and failure conditions), stability and performance is robust (to both failure effects and dynamic variations) and that these properties can be demonstrated with sufficient rigour to satisfy airworthiness authorities.

4.5.1 Determinism

The concept of determinism is used here to stipulate design requirements, as follows:

Design Feature	Requirements
Design Integrity	High *or* Medium
Resource Allocation	Static *or* Static with hard-deadline switching *or* Dynamic with hard-periodic resets[1]
Resource Scheduling	Static *or* Pre-emptive with hard deadlines *or* Dynamic within hard-periodic frames[1]

[1] Only applicable to microprocessor operation

The default requirements would be for [i] the highest level of design integrity, [ii] static resource allocation and [iii] static resource scheduling. In order words, everything about the run-time behaviour of the system is completely pre-determined.

The other design options respect the onward development of dependable computing techniques. It is reasonable to expect that some relaxation of the default requirements will be possible although it must be stressed that this is not an end in itself. For the foreseeable future, system-level resource management will be essentially static. However, if support becomes available for **hard real-time** operation, then pre-emption becomes possible. At processor level, it is possible that optimised VLSI design features (such as pipelining and multiple-level cache) will be used. However, for these non-static features, it will always be necessary to constrain their usage in order to render them open to analysis and test. Without constraints a safety case cannot be constructed.

4.5.2 Robustness

Robustness is concerned with being able to accommodate any unintended behaviour of a system. In practice, this means being able to maintain acceptable stability and performance margins, firstly, under internal failure conditions and, secondly, under external variations (arising either from environmental changes or from an inadequate model of the intended behaviour!).

In the functional architecture, the concept of robust design is concerned with control law development. For a VMS or any other complex, highly-integrated system, the control strategy will be **multivariable**. This demands a new engineering framework for analysis and design, and one which retains the high visibility and common intuition that is associated with classical Nyquist-Bode techniques. This is, in fact, possible to construct if it is recognised that the most important properties of any control system are of signal transmission and **not** those of arcane and recondite mathematics.

The generalisation of classical control requires that, for initial exposition only, certain constraints be imposed on the use of multivariable feedback. Thus, by considering *diagonal control* and *square systems*, a concept of multivariable structure can be formulated which incorporates phase and gain margins as **primary indicators of robustness**. This is justified by a straightforward piece of algebra which shows that the structure of a multi-input multi-output (MIMO) system is described by an equivalent set of single-input single-output (SISO) channels which preserves the rôle of loop interactions. The phase and gain margins are applied to these SISO (or individual) channels

and demonstrate immunity from the effects of dynamic uncertainty and, by extension, structural transitions such as loop failures. Once having established the initial exposition, the constraints can be removed and the analysis can be applied to *non-diagonal* and *non-square systems*.

A conventional model of feedback control is seen in **figure 10**, comprising a 'system' $\mathbf{G}(s)$ and a 'controller' $\mathbf{K}(s)$. The open-loop and closed-loop dynamics are described by the following relationships:

Open-loop System	$\mathbf{y} = \mathbf{G}(s)\mathbf{K}(s)\mathbf{r} + \mathbf{n_P}$
Closed-loop System	$\mathbf{y} = \mathbf{T}(s)\mathbf{r} + \mathbf{S}(s)\mathbf{n_P} - \mathbf{T}(s)\mathbf{n_M}$

where the system output $\mathbf{y}$ is derived from the system input $\mathbf{r}$, process noise $\mathbf{n_P}$ and measurement noise $\mathbf{n_M}$. The transfer function matrices $\mathbf{T}(s)$ and $\mathbf{S}(s)$ are defined as follows:

Tracking Function Matrix	$\mathbf{T}(s) = [\mathbf{I}+\mathbf{GK}]^{-1}\mathbf{GK} = \mathbf{GK}[\mathbf{I}+\mathbf{GK}]^{-1}$
Sensitivity Function Matrix	$\mathbf{S}(s) = [\mathbf{I}+\mathbf{GK}]^{-1}$

For the closed-loop system $\mathbf{T}(s)$, an individual channel can be defined between any selected input-output pair. The feedback loops can then be separated, one belonging to the closed-loop channel and the remainder belonging to the rest of the closed-loop system. By removing its feedback connection, the channel becomes *open-loop*; in fact, it constitutes a special type of open-loop subsystem because it incorporates a complete description of the closed-loop subsystem with which it interacts. The concept of individual channels is absolutely fundamental to multivariable feedback as it provides an intuitive basis for system decomposition, a testable basis for system analysis and a practical basis for system design.

Structural equivalence exists between the tracking function matrix $\mathbf{T}(s)$ and the closed-loop dynamics of individual channels, as shown in **figure 11**. The open-loop dynamics of the i^{th} individual channel can be written in the form $\mathbf{c}_i(s)=\mathbf{k}_i(s)\mathbf{g}_{ii}(s)(1-\gamma_i(s))$, where the term $\gamma_i(s)$ is called the ***multivariable structure function***. The corresponding closed-loop dynamics are calculated as $\mathbf{t}_{ii}(s)=\mathbf{c}_i(s)/(1+\mathbf{c}_i(s))$.

The relationship between uncertainty and robustness is assessed by design margins. The expected frequency response characteristic for an individual channel corresponds to a nominal transfer function model [*cf.* **Figure 12**]. However, there is a range of gain and phase values at any given frequency and a range of possible gain and phase cross-over frequencies. The actual frequency response lies somewhere inside an envelope of possible characteristics. With reference to the familiar Nyquist stability criterion, if this envelope is large enough to enclose the point (-1,0) then the number of encirclements may change, thereby rendering the closed-loop system unstable. This indicates the problem of ***channel robustness***. For SISO systems, this would furnish a complete interpretation of robust control: for MIMO systems, the situation is more complicated.

The term $1-\gamma_i$ is critical in dictating the achievable performance of the individual channel $\mathbf{c}_i(s)$. Its variation over frequency is implied by the polar plot of the multivariable structure function, $\gamma_i(s)$ [*cf.* **Figure 12**]. Uncertainty in $\mathbf{G}(s)$ generates an envelope which bounds the locus of $\gamma_i(s)$. If any part of the envelope encircles the point (+1,0) then there is a problem of ***structural sensitivity*** in that a change in structure can generate additional zeros in the right-half s-plane. Incidentally, this gives rise to a new "Nyquist minimum phase criterion". The effect is pernicious because the resulting loss of phase drives the system unstable and it is particularly awkward because the instability can occur at very low frequencies. Note that, if the γ_i-locus were to pass through the point (+1,0), the channel transmittance would become identically zero at some frequency!

It is convenient to construct a model of *uncertain* multivariable structure by drawing a disc around any given point on the γ_i-locus [*cf.* **Figure 12**]. The centre of the disc gives the nominal value of $\gamma_i(s)$ and the radius gives the lowest upper bound for the uncertainty at that point; a directed line segment drawn to the point (+1,0) defines the gain and phase contributions to the channel transmittance due to the presence of other feedback loops in the multivariable system. The actual value of the multivariable structure function corresponds to a point located somewhere inside the disc. If the disc is 'large' **and** 'close to the point (+1,0)' then the gain and (especially) phase at that frequency become more sensitive to uncertainty, *i.e.* they exhibit a larger range of possible values. *In extremis*, if the disc encloses (+1,0) then the problem of ***phase sensitivity*** becomes acute (up to ±180°). This introduces the possibility of non-minimum phase behaviour which, if it were to occur near the system bandwidth, would jeopardise stability.

Stemming from these insights, three sets of gain and phase margins can be defined for the i^{th} individual channel of a system $\mathbf{G}(s)$:

Channel Robustness Measures	Gain margin of $\mathbf{c}_i$ when $\angle\mathbf{c}_i=-180°$; Phase margin of $\mathbf{c}_i$ when $\lvert\mathbf{c}_i\rvert=1$.
Structural Sensitivity Measures	Gain margin of γ_i when $\angle\gamma_i=0°$; Phase margin of γ_i when $\lvert\gamma_i\rvert=1$.
Phase Sensitivity Measures	Gain and phase margins of γ_i when $\angle\mathbf{c}_i=-180°$; Gain and phase margins of γ_i when $\lvert\mathbf{c}_i\rvert=1$.

These are shown schematically in **figure 13**. The channel robustness measures are akin to the classical phase and gain margins for stability robustness; structural sensitivity and phase sensitivity are indicators of performance robustness. If both structural sensitivity and phase sensitivity are benign, then the classical phase and gain margins associated with the individual channel are valid measures of channel robustness (provided, of course, that the usual 'gradient rules' are observed at the gain and phase cross-over frequencies).

4.5.3 Testability

The system design must be capable of being tested at a number of levels and, therefore, appropriate access mechanisms must be provided by design. Specific requirements exist for tests to be performed in the following circumstances:

- **design and development**
- **flight clearance**
- **maintenance**
- **pre-flight**
- **in-flight**

With increasing complexity of system design, the rôle of simulation will become more and more significant, both in establishing the expected behaviour of the system and in determining the most appropriate test procedures. This involves making assessments of failure effects and worst-case interactions in order to ensure adequate test coverage.

In the context of the present discussion, it is appropriate to concentrate on the relationship between testability and simulation. The use of simulation tools for VMS design and development enables a much greater consideration of different system options and a more rapid assessment of different optimisation strategies. The principal benefit lies in the ability to perform extensive analysis and to generate benchmark results in support of flight clearance activities. Note that simulation will **not** in itself reduce development timescales!

It is possible to construct simulation models at all levels of architectural abstraction but, in practice, it is probably cost-effective to stop at the level of process architecture. A staged approach is necessary, establishing the viability of an overall system concept model first of all and, then, proceeding in a modular fashion to substitute more detailed models where required for the particular development activity being undertaken. Concept models are especially useful because they convey basic information (*e.g.* parametric trends, dominant dynamics) without undue elaboration. Subsequent tests must verify that model substitution, while giving more accuracy results, does not fundamentally alter the conclusions regarding the overall system concept.

It should be recognised that, from the various viewpoints which overlook VMS [*cf.* **section 3**], the structure of the system is parallel (or concurrent). Considerable progress has been made in understanding the issues involved in constructing large-scale diverse simulation models using parallel machines. This technology can offer for the first time at an affordable price a real-time simulation capability which has wide applicability across aircraft systems. More work is needed, however, in order to satisfy demands for generic simulation platforms which can access graphical notations (such as those generated using MATRIX_X® or EASY5®) and map a simulation model on to a network of processors, *e.g.* transputers. This will have a profound impact on productivity of so-called "simulated engineering" and, at last, enable the development of a proper *Virtual Rig* environment.

Because simulation will play a very important in VMS design decisions, new concerns are being raised about *Dependable Simulation*. A system architecture (to any level of detail) can be encapsulated as the functional architecture of a simulation. The subsequent design of that simulation can be interpreted as a hierarchical abstraction, in exactly the same way as for system design [*cf.* **section 2.2**]. The resource utilisation contained in the process architecture will include facilities such as a Graphical User Interface (GUI), Computer-Aided Engineering (CAE) tools and general-purpose interfacing for "Hardware In The Loop" testing.

The concept of system integrity which is relevant here is perhaps best described as *Design Critical*. This implies a particular type of high integrity system for which 'unacceptable' means 'incorrect calculation', resulting in incorrect design decisions or invalid clearance (with potential safety implications). Using the existing criteria, the formal options for design-critical system implementation are usually considered to be [i] a medium level of design integrity and [ii] fail safe response. These are justified, respectively, because simulation must always be reinforced by independent calculation and because continued operation (due to an undetected failure) leads to an unacceptable outcome (*i.e.* wrong results). There is no requirement for a fail operational response: on the contrary, there is a positive requirement to stop the simulation when a failure occurs in order to generate diagnostic information.

4.5.4 Flight Clearance Activities

Having formulated the working definitions of determinism, robustness and testability, then flight Clearance can be shown to depend upon:

Design
Analysis
Testing

Clearance or "proof of operation" is not a single activity, performed once, but is made up of many activities, performed throughout a programme and pervading every facet thereof. Some further brief comments will suffice in order to highlight some of the key aspects.

Design requires a well-defined methodology and good configuration control. Although it is accepted that practical design proceeds middle-out, it must conform to the well-established notions of structured decomposition and modular partitioning. To this end, the widespread use of structured semantics (for high-order language programming) and graphical editors (*e.g.* for simulation block diagrams) is of great help. Potentially, the use of object-oriented languages (such as C++) will have a profound effect on engineering simulation and design.

Analysis must be performed in order to show that a system is acceptable both in terms of the control design (adequate gain and phase margins, *etc.*) and in respect of the hardware design (failure modes and effects, *etc.*). Software items must be subject to appropriate analysis to verify that they are structured in a manner which is satisfactory for safety-critical applications. Typically this would include examination of program structure, data and control flow, and ideally would be performed by same form of computer-based tool, such as SPADE®. It is essential that analysis proceed in parallel with design; it is not an "incremental" activity done later.

Testing is usually understood to be the "verification" that a design is correct and the "validation" that it fulfils its specification. Unlike analysis, which generally takes place on a general-purpose workstation, testing in support of flight clearance has to make use of actual flight-standard hardware or, at least, its functional equivalent. Simulation can assist test activities by providing an independent model against which the operation of the target system can be compared. It can also be used during the design stage to gain an insight into system operation, particularly in the presence of systematic faults.

Due allowance must be made in system design as to the intended purpose of a system in order to make testing practicable, rigorous and cost-effective. Some past designs, although nominally satisfactory in functional terms, were almost impossible to test because testability was not considered at the design stage. For the complex and highly-integrated systems envisaged for the future, such omissions might mean that systems would be completely impossible to test to any degree of confidence. Thus, VMS implementations must be provided with features which enhance testability and enable systems to be constructed in a staged manner as hardware/software becomes available during development.

5 Where are the Challenges?

Traditionally, for relatively simple systems, development has been split into two disciplines, namely *Control Law Design* (servo loop design) and *System Design* (including software). Future systems will not be so convenient. Proper operation, particularly in the presence of one or more failures, requires

the design to be properly understood and coordinated if the criteria of *Determinism, Robustness* and *Testability* are to be met. This in turn raises challenges in a number of key research areas. These are summarised below.

A3 Operating Systems
Research into operating system concepts is required urgently. As currently conceived, A3-based systems cannot support safety-critical applications as they do not provide [i] hard real-time scheduling or [ii] allocation services for segregation of system resources. "Hard real-time" is an essential requirement for determinism; this is an issue for both system design and system simulation. The "segregation" issue could be resolved by modifying the A3 hardware concept.

Analytical Control Theory
An exhaustive assessment of robustness can be performed on multivariable control systems, using phase and gain margins. This provides immunity from the effects of dynamic uncertainty. Further work has provided the extensions necessary to handle loop failures and, also, systematic changes due to moding and logic. Current priorities for VMS flight clearance are concentrated on non-robust failure modes and "worst case" effects arising from multivariable structure, nonlinear dynamics and time variance.

'Virtual Rig' Simulation
The reliance on simulation technology is likely to increase significantly as a result of VMS development, because of factors like "size", "connectivity" and "optimisation". It is certain that much of the evidence in support of flight clearance will be computer-generated and will involve diverse models and sophisticated analytical tools. The issues of *Virtual Rig* and *Dependable Simulation* are closely related and there is a clear need to establish industry standards for development and qualification of commercial simulation and support tools. Note that the objective is not to enforce the use of Commercial Off-The-Shelf (COTS) products which are inadequate, but to encourage the creation and adoption of appropriate standards against which future COTS products can be qualified for safety-critical system development.

6 Conclusion

VMS concepts contain complexity and diversity. They are subject to uncertainty, both because the integration issues are not particularly well understood and because the applicable technologies have not yet been fully defined. It is certain that partitioning must be adopted for development in order that the specification, design, implementation and test activities for the various parts of the system will be tractable.

The hope is that a push will be made towards the creation of a "modular" flight clearance procedure. Recent work on architectural definition (especially A3) and object orientation indicates that this should be possible. What is needed is a concerted effort to formalise qualification requirements at system-element level, within an overall framework that allows flexibility in connecting system elements and traceability between *internal* failure modes and *external* hazard identification. This would allow system configurations that are non-permanent, possibly through the use of dynamic switching, as discussed already.

Simulation will be vital in this context although gaining acceptance of the underlying philosophy will pose perhaps the greatest challenge of all. The implications are far-reaching and influence many requirements, such as

- **Safety**
- **Legislative**
- **Quality**

The top priority is to sponsor work which will generate a draft standard on *Certification Considerations for Modular Aircraft Systems*, taking into account the decomposition of system development activities, the rôle of modelling and simulation, independent qualification testing, compatibility of system failure models, integration of system design data, flexible allocation of system resources and so on. The recent contribution by the SAE Systems Integration Requirements Task Group, dealing with 'complex and highly-integrated aircraft systems', is a most welcome first step. However, the clearance philosophy must evolve very quickly if it is to keep pace with technology and if it is provide a legal basis for the certification of aircraft systems.

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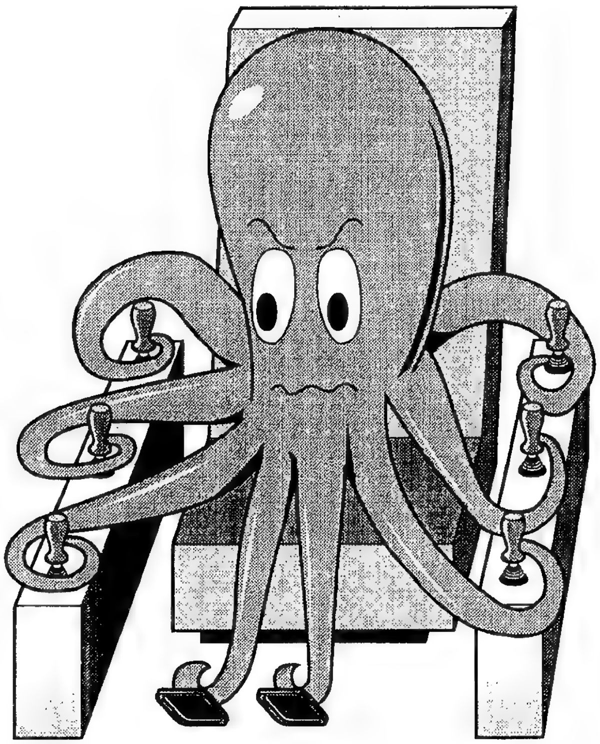

Figure 1 A New Breed of Test Pilot?

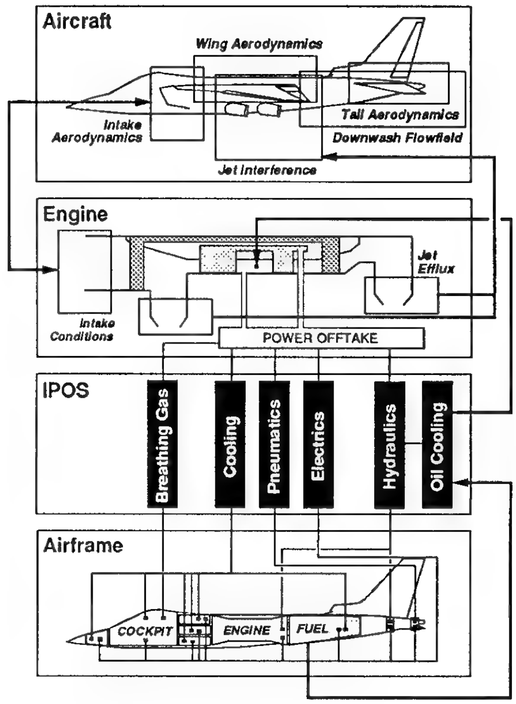

Figure 3 Physical Viewpoint

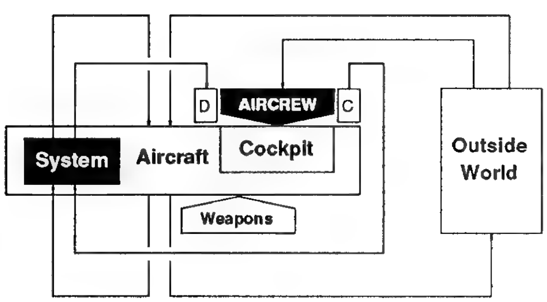

Figure 2 Aircraft Viewpoint

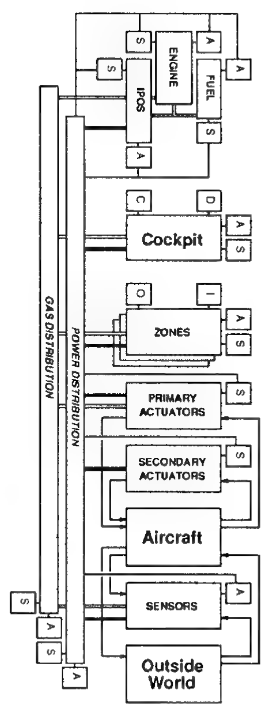

Figure 4 Equipment Viewpoint

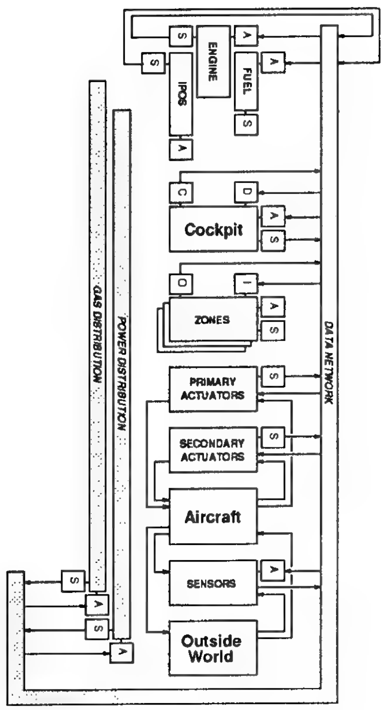

Figure 5 Communication Viewpoint

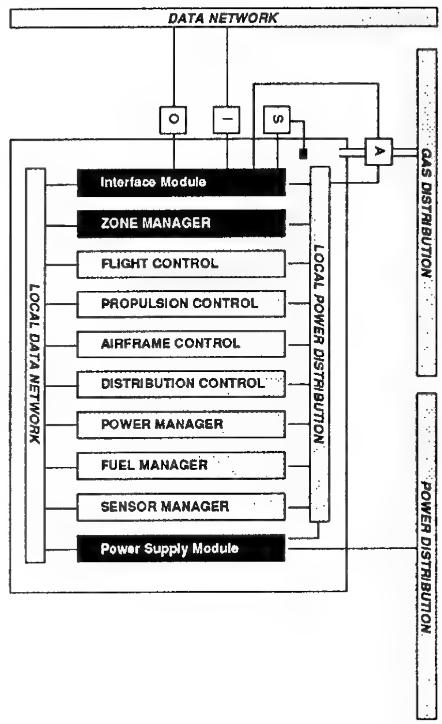

Figure 7 Processing Viewpoint

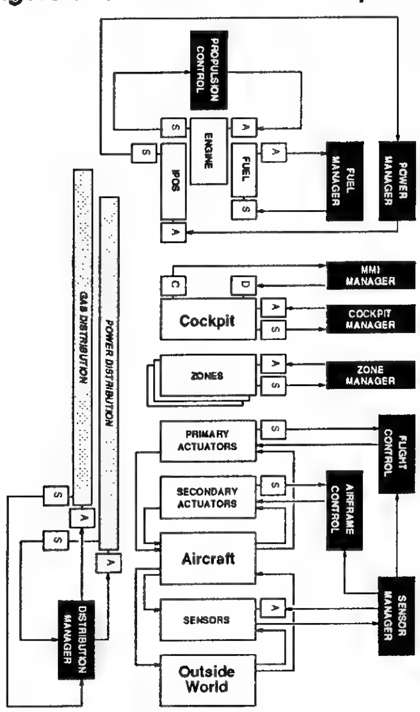

Figure 6 Functional Viewpoint

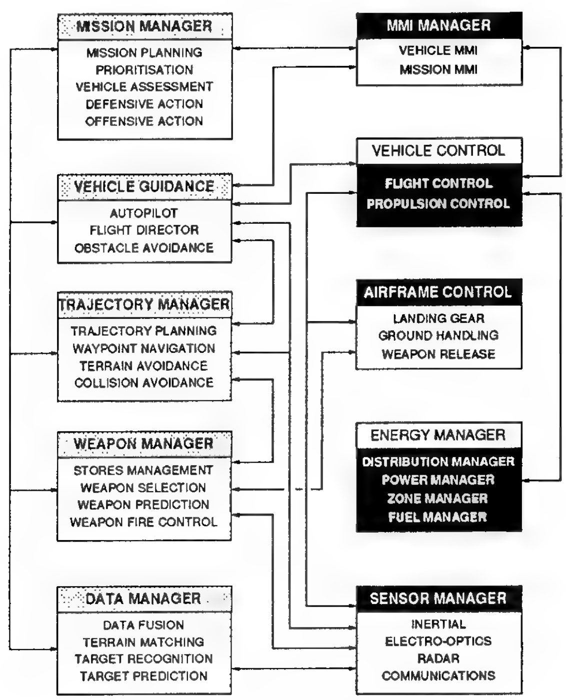

Figure 8 Integration Viewpoint

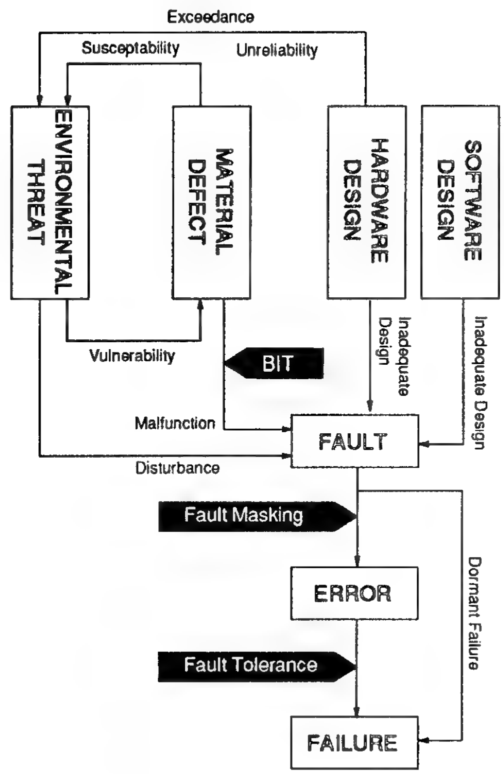

Figure 9 Fault Propagation Model

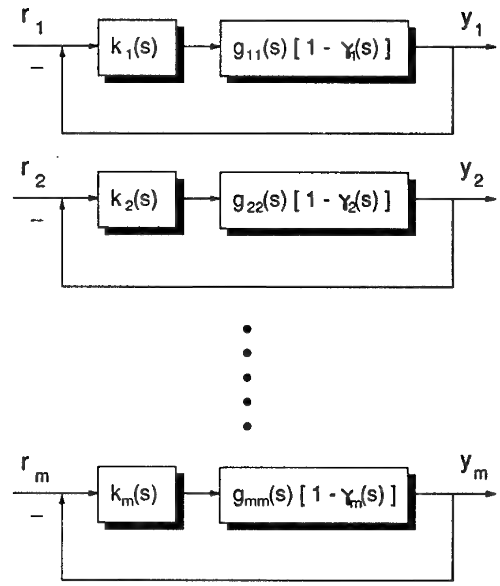

Figure 11 Individual Channel Decomposition

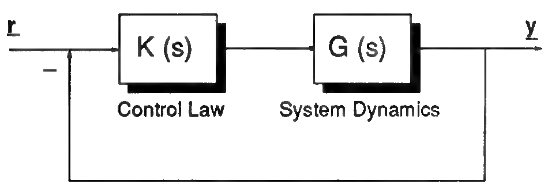

Figure 10 Automatic Feedback Control

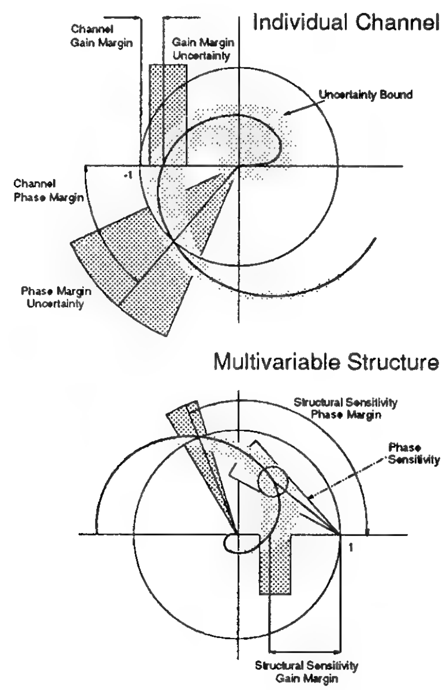

Figure 12 System Uncertainty

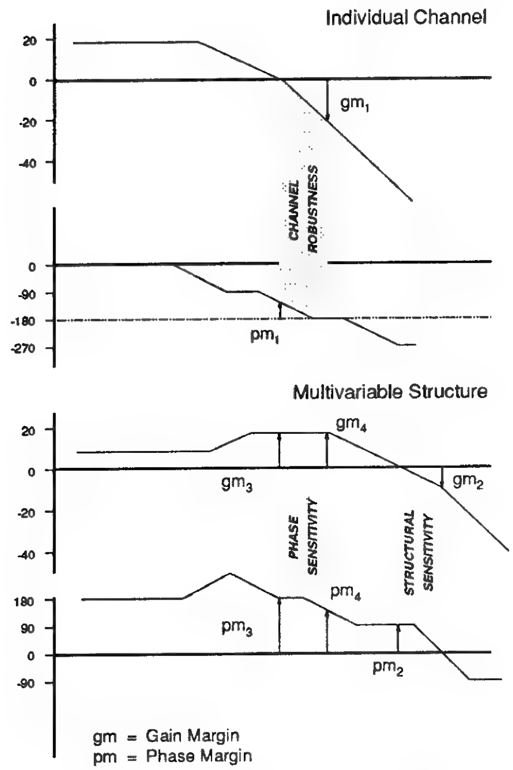

Figure 13 Phase and Gain Margins

THE DUTCH NATIONAL SIMULATION FACILITY: ADVANCEMENTS IN SIMULATOR TECHNOLOGY AND APPLICATION

by
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1. SUMMARY

The Dutch National Aerospace Laboratory NLR has developed during the last three years an advanced Full Mission Simulation capability for fast jet fixed wing and rotary wing aircraft. This Full Mission simulator, named the National Simulation Facility NSF, is created for research in training methodologies, investigation of simulation and simulator requirements for specific training tasks and to support industrial development of cockpit and aircraft systems. The current capability of the simulator focuses on the F-16 Mid-Life Update configuration, but will be extended to accommodate manned helicopter simulation later this year. The latter will be directed towards the recently (by the Dutch Air Mobile Brigade) procured Boeing CH-47D Chinook medium-heavy transport helicopter, and the McDonnell Douglas AH-64D Apache attack helicopter.
This paper will address the various technical aspects of the National Simulation Facility.

2. INTRODUCTION

The National Simulation Facility (NSF) which has been developed at the Dutch National Aerospace Laboratory NLR situated in Amsterdam, is an extension to the already existing NLR Research Flight Simulator. This simulator is operational since 1976 and is mainly active in the field of civil oriented research simulation. However, military simulation could also be accommodated, illustrated by the fact that the mechanization of the digital flight control system of the Israel Aircraft Industries LAVI fighter aircraft was designed and refined on this same facility.

During the last years the need for research into training methodologies, simulation and simulator requirements, pilot workload in various tactical situations has become more and more important, which led to requirements to extend NLR's simulation capabilities.

Not only should this extension follow the Mid-Life Update of the F-16, but it should also be possible to simulate rotary wing aircraft. Even, when the need was felt, it should be possible to simulate fast ships or land vehicles.

Financed by the ministries of Economic Affairs and Defence, the Royal Netherlands Air Force and NLR's own research budget, the NSF was developed by NLR researchers in a relatively short time span of three years.

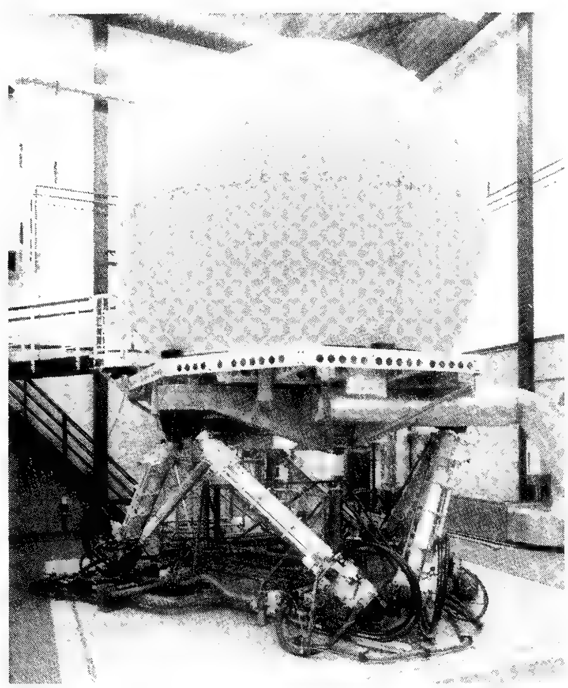

Fig.1: The National Simulation Facility NSF

Paper presented at the AGARD FVP Symposium on "Flight Simulation — Where are the Challenges?", held in Braunschweig, Germany, from 22-25 May 1995, and published in CP-577.

3. PURPOSE OF THE NSF

The National Simulation Facility is designed as the primary facility in the Netherlands for advanced simulation and training research and development, and for the (inter)national aerospace industry to have an instrument to evaluate and test aircraft (sub)systems, hence its name. The NSF focuses in its applications primarily on Defence related research:

- the concern on growing pilot workload due to the increasing complexity of avionic systems needs to be addressed in the early stages of system design. To understand and assess pilot workload during tactical missions and combat, controlled conditions must be created which can replicate the situations encountered in current fast jet and helicopter aircraft.
- Aircraft and avionic manufacturers must integrate their concepts in the earliest possible moment during aircraft design. Early pilot in the loop evaluation of these concepts can only be achieved in a simulator capable of integrating real and emulated avionic systems. The NSF is designed to integrate real avionics or to simulate it through its software counterpart.
- Training systems should not represent a mere replication of aircraft systems and their functions but should be precisely designed instruments to increase the pilot's efficiency when flying his aircraft. Research into the "unknowns" of simulator training is currently a "hot topic". Various (inter)national programs like the EUCLID CEPA 11 address simulator and their benefit in training. The NSF has a significant role in CEPA 11.

From these and other purposes the NSF was put forward by the Dutch Government as a prime requirement. Making maximum use of existing facilities, infrastructure and expertise, NLR was put forward as the preferred base for the NSF.

The aim for NSF is to create a full mission, both manned F-16 Mid-Life Update and helicopter simulation capability for research and development. The top level specifications could be defined as:

- The facility should be capable to perform, on behalf of Lockheed's F-16 Mid-Life Update codevelopment programme, one of the final functional cockpit mechanisation checks before actual flight testing of the F-16 MLU aircraft;
- Simulations must support air-to-air, air-to-surface, low-altitude high-speed missions with a maximum of realism. This implied that not only the visual system should have a very high fidelity, but also that F-16 weapons, avionics systems and the mission environment should be modelled with great precision and realism;
- Simulator investigations concentrating on human factors is considered to be one of the prime issues of the facility's capabilities: research into training and training effectiveness, assessment of pilot workload during simulated combat missions, etc. This implied that the NSF must be capable of integrating physiological measurement equipment.
- Assessment of simulator training effectiveness and (training) simulator component requirements should be possible by selective 'degrading' of its components;
- Simulation of avionics should support integrating both aircraft equipment through its standard interface ("hot bench") and its functional software equivalent;
- The design and development should include the future growth to enable helicopter simulation;
- All hardware and software components should be designed in such a way that maximum interchangeability with the other NLR research flight simulator would be ensured.

A great many more requirements could be presented here, but this would distract the reader from the more essential information in this paper.

4. FULL MISSION SIMULATION IN A RESEARCH ENVIRONMENT

4.1 Introduction

A flexible and modular setup of hardware and software components can be regarded as the conceptual heart of every research simulator. The components by itself show in some cases already unique features. One can see this at the various Research Flight Simulation establishments in Europe and beyond. The British Defence Research Agency created for advanced helicopter research their Large Motion System, a facility identifying the very large vertical excursion

requirements for helicopter simulation.

4.2 NLR's Research Flight Simulator
NLR operates a research flight simulator since 1976. At that time simulations were carried out with a generic fighter (modified F-104 "Starfighter") cockpit which was placed on one of the first platform motion systems with hydrostatic bearings. Some years later a (DC-7) transport cockpit was refurbished to accommodate multi-crew experiments. This cockpit could be exchanged with the generic fighter cockpit and placed on the motion platform. Both the transport and the generic fighter cockpit have been modified during the years following to the ever changing cockpit technology. Currently (fig.2) the transport cockpit features a lay-out to functionally simulate a Boeing 747-400 or similar "glass" cockpit aircraft, including Control & Display Units (CDUs) for operating the Research or Experimental Flight Management Systems, touchpads for Air Traffic Management Datalink communication etc. This simulator has recently been used in a number of experiments for conceptual evaluation of using ATC-aircraft datalink, evaluations of Take-Off Performance Management System and investigations into the establishment of handling qualities for fly-by-wire large transport aircraft. Especially in those projects where operationally realistic flights are essential to the outcome, a civil equivalent of a full mission scenario must be created. This includes radio traffic, genuine ATC messages and directives, visual converging aircraft (to react on TCAS-messages), proper radio and beacon frequency selections etc. Apart from simulating emergency and system malfunction conditions, this Research Flight Simulator could also be used for training: the big difference to a training simulator, however, being the very modular and flexible software and hardware setup. The simulator can be changed from a Boeing 747-400 to a Fokker 100 in a couple of hours, or from a traditional B-747 equipped with Primary Flight and Navigation Displays to a fly-by-wire aircraft operated by sidesticks and equipped with CRTs displaying information in three dimensions.

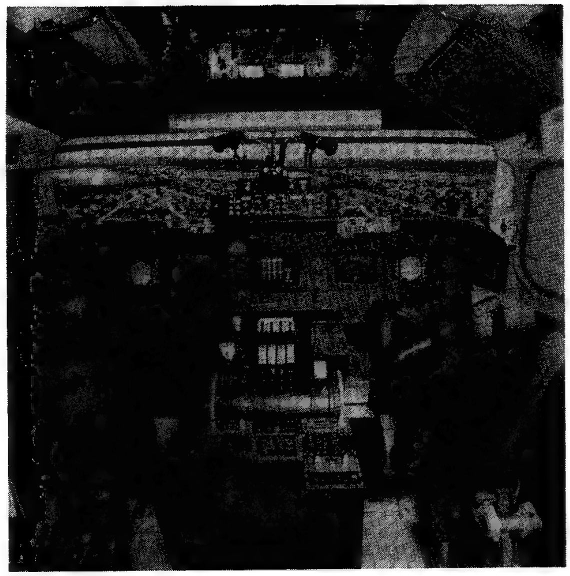

Fig.2: Research Flight Simulator RFS

4.3 Research applications for the NSF
The NLR National Simulation Facility NSF was designed for fast jet and helicopter simulation research. Based on the specifications mentioned earlier, several concepts of building the NSF were possible. One of the most important requirements is the ability to change the facility for different research objectives. This includes exchanging cockpits on the motion system, change the flying characteristics of the aircraft, change the interior of the cockpits and/or change the way the information is presented to the pilot. In most cases this prohibits the use of the actual aircraft instruments. The capability to adapt them to the specific simulation requirements is essential. For instance, the Multi Function Displays in the F-16 cockpit are driven by graphics workstations instead of the Modular Mission Computers HUD Electronics Unit. The latter provides fixed, non-changeable (currently) monochrome display symbology. A requirement for future research, however, is the ability to colour symbols and investigate the human factors implications of it.

The interaction of the pilot with his environment is a major research topic. Environment in this context must be seen in a wide sense: from situational awareness issues during specific combat missions to definition of skill acquisition in a training task analysis.

- In the ongoing EUCLID (EUropean Cooperation for the Long term In Defence) programme, the NSF is scheduled in two Research and Technology Projects: RTP 11.1 on "human factors" and RTP 11.2 on "simulation technology". Both RTPs consider the lack of knowledge in the current (pilot) training processes an area worth looking into in great detail. Basis for both RTPs is the definition of "skill" and skill acquisition and the way it can be influenced by training, both in the real aircraft and in the simulator. The definition of objective measures and subsequently the definition of the training task, its context and the technology to be used is the prime outcome of these RTPs. The NSF will be used as the validation tool, as it is considered to be one of the most advanced (research) simulators available at present. Influencing the training context, being for instance the size of the field of regard or the size of the field of view of the visual scene, is of utmost importance. Although many studies in the past have already been performed with reconfigurable simulators, the NSF combines for the first time high performance cueing in motion (both platform and direct body cueing), full field of regard high resolution visual and advanced audio cueing in a full mission environment.
- Already mentioned is the participation of NLR in the Lockheed F-16 MLU codevelopment program. The NSF will be used to perform a cockpit mechanization checkout to look into the various specific European MLU-unique items. In the checkout simulations, pilots from five nations (USA, Belgium, Norway, Denmark and The Netherlands) will evaluate whether all the changes made in the avionics functionality are implemented correctly and whether the avionics meet all the specifications.

5. INNOVATIONS IN RESEARCH FLIGHT SIMULATION

5.1 Introduction

Conception of the NSF took place some five years ago. Ideas were formed and brain storm sessions with the operational air force community took place to establish the NSF's prime requirements. From these discussions it became clear that development of the NSF could not be regarded as a "normal" extension of NLR's Research Flight Simulator. The growth foreseen in software code and its processing due to the requirements of needing a full avionics suite and a full mission environment, had an enormous impact on the existing infrastructure. For instance the computer systems resources should quadruple (memory, throughput, input/output, disk capacity etc.), which could not be handled within the same host computer operated at that time. The TV-modelboard visual system could hardly be used for the fast flying and fast manoeuvring F-16 fighter: it not only lacked the necessary response speeds, but more important, the visual field of view of 40 x 30 degrees was deemed insufficient.

However, not all required components for the NSF would have to be newly developed or bought: the six degrees of freedom platform motion system, designed for simulation of fast jets and helicopters was already operational. Large parts of the F-16 simulation software, the aerodynamics, flight control system, engine and undercarriage models had already been validated. And last but not least, the expertise and knowledge of our simulation group played a major contributing factor in the subsequent development period.

At the moment the required funds for the NSF development were granted, a large scale system definition task took place which final outcome can be observed in the components, in detail described below.

5.2 Computing Technology

One of the first (new) systems to be decided upon was the simulation host computer. Having operated a Concurrent MicroFive computer with its dedicated, proprietary operating system for many years, the need was felt to change to UNIX-based computers (the Concurrent is still being used for the other civil-based Research Flight Simulator -RFS-). After a careful selection process, the Silicon Graphics Challenge L was chosen of which two systems were procured. For many years, software development and real-time operations were carried out on one computer system with one very big drawback: during busy simulator experiment periods software development would almost come to a standstill. For the NSF two identical Challenges are used, one of which is dedicated for software development, the other is dedicated for real-time operations. The four MIPS R-4400 processors in each Challenge operating

at 100 MHz have sufficient computing power to run the entire F-16 simulation programme at nominal 50 Hz update rate (on only one processor). For software development we decided to change from the standard ASCII terminals to an "X-windows" environment.

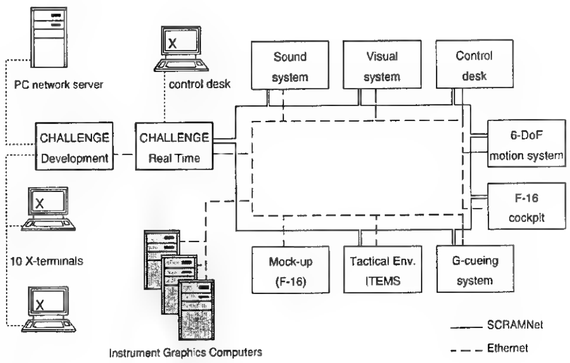

Fig.3: NSF Flight Simulator Interface System

Changing to another computer system led to other implications. All RFS simulator hardware systems are connected to the Concurrent via dedicated I/O channels. The digital-analog and other converters are part of this host computer and can not be easily reconfigured. A more user-friendly I/O-system was, at the beginning of the NSF-project, already in the process of being designed. Its concept: each major hardware system (visual, motion etc) receives its data through a node connected to a networked fibre-optic, digital interface system. Each node has a processor which would pack and unpack the data necessary, and performs calibration type of calculations. Essentially this interface concept has been used in the design for the NSF (fig.3). A SCRAMNet based, fibre-optic network connects all major subsystems, next to a dedicated Ethernet. The SCRAMNet-system operates as a "reflective memory", thus sharing almost instantaneously the relevant data between the various (front-end) computer systems. Sharing of data occurs at a speed of 6.4 Mbytes per second for the time being and at the current update rate fast enough to satisfy our requirements. An important lesson learned using this concept is the fact that a computer's internal memory-to-memory transfer speed, especially with large amounts of data to be transferred, can become a bottleneck.

For real-time interfacing with the graphics computers and for non-realtime interfacing with all other computers, a dedicated Ethernet is used. The graphics computers are used to generate the various displays for the F-16 cockpit and control desk, including the Multi-Function Displays and the Head-Up Display. Instead of routing dedicated RGB-cables to a specific location, and thus creating a non-modular use of expensive graphics computers, a Video Distribution System was created. This system connects, through a cabinet, each graphics computer with a display location. In this cabinet, however, connections can be rerouted. A multitude of (Silicon Graphics) graphics computers are used: from the IRIS 4D/85, -210 and 310 VGX (equipped with video-splitters) to the more current Indigo W8C and Extreme.

5.3 Visual Cueing

Probably the single most important attribute in a simulator is the way the pilot (or driver) receives his visual information. Taking into account the required research applications, it proved to be difficult to define the requirements for the NSF visual system. The technical solutions available for presenting a 360° field-of-regard Out-of-the-Window (OTW) image to the pilot did not have sufficient overlap. The prime requirement could be narrowed down to the following: does the use of operational equipment, normally worn by the pilot, have to be considered of more importance than a high-resolution, high-brightness image. Ergo, the choice between dome or helmet mounted display. For the NSF the decision was made for a dome with a head-slaved area-of-interest projection display system, the best compromise between using operational equipment versus brightness and resolution.

The NSF visual system contract was awarded to Evans & Sutherland, which could offer a total, integrated image generator and display system. The head-slaved projection system, called VistaView®, offered an "affordable" compromise between field of regard, resolution and brightness. Eye-tracking was not really considered an option. Although the Link-Miles ESPRIT simulator was already equipped with eye-tracking equipment, we didn't feel sufficiently confident to incorporate eye-tracking at that time.

The image generator, a three channel ESIG-3000® AT/GT combines the latest technology available within one system. Two channels are configured to handle 1000 polygons in the inset and 3000 polygons in the background, thus giving a balanced polygon density over inset and background. The third channel is used for sensor simulation. Either an optical sensor (including zooming features) or an infra-red sensor can be simulated.
Quite unique is the capability to modify (through datafiles) the IG throughput delay (which can be lowered to 40 milliseconds delay) and the distribution of polygons over inset and background.

The projection system displays a head-slaved background (142 x 110 degrees) and a head-slaved inset (51 x 36 degrees) on a 16.6 feet diameter graphite composite dome. Figure 4 shows the area-of-interest concept.

Both the images for background and inset are pre-warped in the IG, where also a dynamic non-linear image mapping function corrects for not having the exit pupil of the optical system in the centre of the dome. After de-rotation the single image is projected by means of a servo-controlled lens. Capability of the servo system is better than 4800 deg/sec^2 and 1500 deg/sec, which for future growth allows the servos to track the eye line-of-sight for variable acuity IG techniques.

For various research studies it should be possible to change the field of view of the system, a feature which can be implemented by changing an optical element in the VistaView® and reconfiguring the IG through its onfiguration file. In this way the FOV can be changed from the nominal 120 degrees in azimuth to 180 degrees. The elevation FOV changes accordingly.

The dome has a high-gain coating (gain 5) which was felt as a good compromise between brightness fall-off and the available brightness (measured 6.8 ftL) with a contrast ratio of 54:1, at the pilot's eye point. Although the dome consists of 24 sphere-parts, no seam can be observed through the use of special coatings and integration techniques.

During the design and testing phase, special attention was paid to the required stiffness of the projection system and dome. No relevant resonance frequencies due to the imposed frequencies of the platform motion system, should be noticeable in the region between 0 and 25 Hz. This was a very tough requirement for the projection system and could only be satisfied after some mechanical modifications had been made to its pedestal and the attachments to the platform. The dome, however, has an even higher stiffness: a measured first resonance mode of 80 Hz.

5.4 Motion cueing
Much can be said on the relevance of motion cueing in fast jet flight simulation, a difference can be made, however, for training simulators and those to be used for research and development. Based, amongst others, upon our experience from the IAI-LAVI digital flight control law development in which the necessity of platform motion was proved for evaluating handling qualities, a clear need for a platform motion system was present.

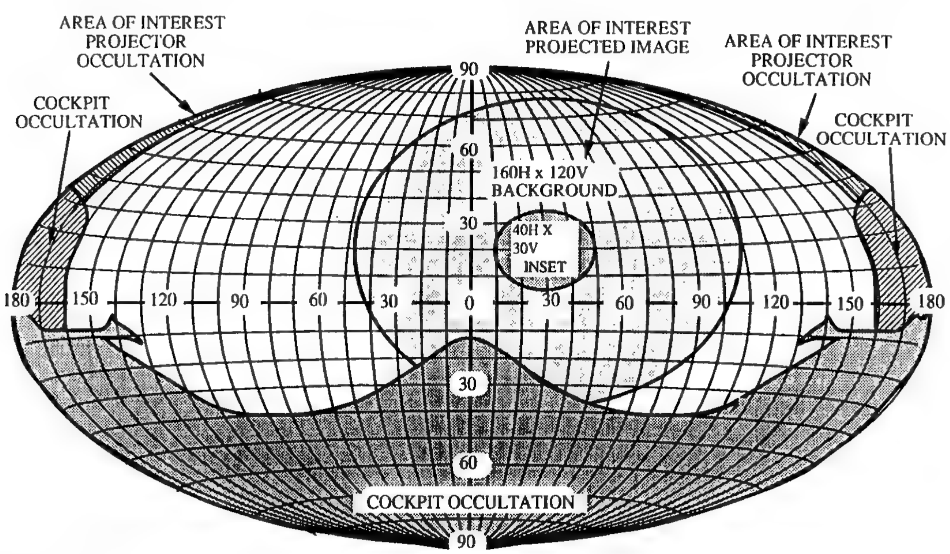

Fig.4: Area-of-Interest Concept

Fortunately the NSF could be built on the synergistic six degrees of freedom motion system already made on specific NLR requirements by the Dutch firm Hydraudyne. The NSF 6-DoF system can be regarded as a high-performance system, its main specifications listed in table 1.

Table 1: NSF 6-DOF motion system specifications

	displacement		velocity	acceleration
	pos	neg	(pos/neg)	(pos/neg)
longitudinal	1.72	1.34 m	0.8 m/s	8 m/s^2
lateral	1.39	1.39 m	0.8 m/s	8 m/s^2
vertical	1.01	1.14 m	0.8 m/s	10 m/s^2
roll	30	30 deg	30 deg/s	200 deg/s^2
pitch	29	29 deg	30 deg/s	200 deg/s^2
yaw	40	40 deg	30 deg/s	150 deg/s^2

fully hydrostatic actuators

band width: 45 degrees phase lag at 4 Hz

Nevertheless, for fast jet (and helicopter) simulation some additional motion cueing is necessary. The high-g environment in which a fast jet pilot operates during attack missions can be regarded as a "disturbance" to his normal behaviour. Apart from a human centrifuge, some sort of equivalent flight perception can only be generated by a G-cueing device. Because of latencies normally found in "older" g-seats due to the pneumatic systems used, specifications for the NSF g-seat stipulated very low (less than 70 milliseconds) delay.

The contract for the NSF G-cueing system was awarded to Sogitec, which develops and integrates the system based on NLR-specific requirements. It will consist of a G-seat, an anti-G suit system, helmet loader and lap-belt restrictor. A Partial Pressure Positive Breathing system had also been considered, but the medical implications to use it on "real" pilots outweighed its usefulness.
Integration of the G-cueing system will take place in the beginning of 1996.

5.5 Cockpit fidelity

For the large amount of human factors studies to be performed with the NSF, a choice was made for a high fidelity cockpit. Instead of generic controls and displays, a dedicated cockpit is needed when training studies involve parameters like pilot workload.
An <u>F-16 MLU cockpit</u> was procured from Lockheed Fort Worth Company by the Royal Netherlands Air Force (RNLAF). The NSF F-16 cockpit consists of a real aircraft section, adapted by Lockheed for simulation purposes and for placement on a motion platform. Most of the instruments, displays and controls are exactly as in the aircraft, however some specific instruments (like altimeter) had to be exchanged by special simulator instruments.

Another important aspect of creating a high fidelity environment is the ability to reproduce correct communication and aircraft related sounds. The <u>sound generation system</u> is a digital system based on the Paradigm Emax II sound synthesizer and state of the art digital sound processors integrated through a SGI-Indigo with AudioWorks and built by the Dutch firm CHeSS. The sound system not only performs all sound generation for the F-16 cockpit such as aerodynamic hiss, engine and Voice Message Unit sounds, but handles also all communication routing between cockpit, control desk, mockup and experiment controller.
The sound system is prepared to handle three dimensional sounds, which will possibly can be a next step in lowering pilot workload and improving situational awareness in the aircraft.

5.6 Simulation Software

Incorporating the necessary innovation in simulation software for the NSF led to one of the project's critical development items. Having made the decision to change the host computer and the type of operating system, the NSF projectteam faced a major redesign of the existing real time scheduling software and the existing (simulation model) software development tools.
From the end of 1992 until the beginning of 1994, NLR researchers together with subcontractors Fokker Space & Systems and BSO/Origin developed, a completely new software tool, called PROSIM (Programme and Real time Operations Simulation support tool) (Ref. 3). PROSIM incorporates the latest information

technology on real time scheduling and software development.

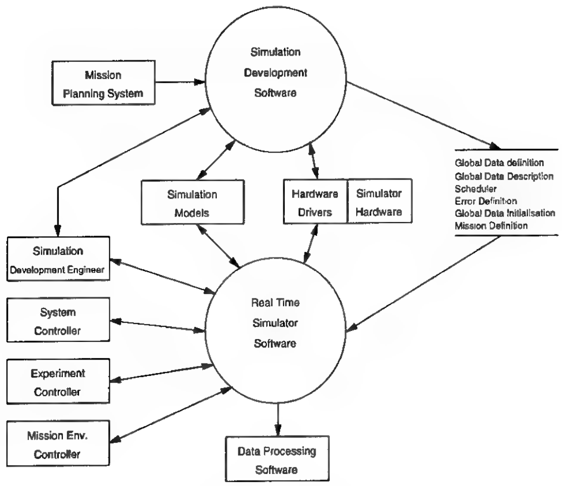

Fig.5: Top-level functionality of PROSIM

A completely new aspect, compared to operating the RFS, was the necessity of having a full avionics simulation suite for the NSF. During the entire existence of the NLR Research Flight Simulator, no detailed functionality of all of the aircraft avionics systems was needed. To be able to develop this avionics simulation software for the F-16 MLU, engineers from LFWC's Flight Simulation Laboratory were contracted to assist the NSF team. Large portions of the avionics software used at the Lockheed simulation facility were transferred to the NSF, thereby creating a nearly 100% concurrency of the NSF with the MLU aircraft.
Before converting and integrating this software, a special team had laid out a design to be able to incorporate an avionics "hot bench" functionality. When available, the NSF can operate real aircraft avionics or switch to its software counterpart; whatever is needed for a specific experiment.

To have all decentralised computer systems operate in a coherent fashion, proved to be no sinecure. Although most interface computers operate with identical processors and software, each computer runs, in a sense, autonomously from the host: the reflective memory data being the only part shared at the same moment. Specially during the first days of operating in real time mode, the various interface computers had a life of their own. The "Power ON/OFF" button had to be used on many occasions. However, these teething troubles are now slowly being solved and done with.

The predicament "full mission" for a simulator can only be given when not only the aircraft's internal systems are correctly simulated to respond on external threats, but also when the external environment reacts in the same correct fashion. An aircraft operating below a certain altitude and making use of surrounding high terrain can shield itself from being detected by missile sites. The NSF makes use of terrain masking models, having been converted from the visual database, to make ownship and threat line-of-sight calculations. This data is also used by ITEMS, the "Interactive Tactical Environment Management Simulation" package of CAE Electronics. ITEMS was procured to handle all threat, target and networking (including DIS) computations. Operating on a stand-alone SGI Indigo W8C, it hooks in the simulation software through a SCRAMNet reflective memory interface.

6. NSF RESEARCH PROJECTS

Current research experiments scheduled for this year focus both on pure research and system development. It is paramount to our facility that all new systems incorporated in the NSF function in a fully synchronized manner. Correct functioning of the various motion control and wash-out schemes have to be established for various flight conditions. Also all subsystem computational delays and the total system time delay will be researched.
In the second part of this year a, government funded, technology demonstration project will show the benefits and drawbacks of using speech recognition and commands in the F-16 MLU aircraft operating in different threat conditions.

During 1996, the NSF will be heavily involved in the EUCLID CEPA-11 programmes RTP-11.1 and -11.2, amongst others.

7. CONCLUSION

Development of the National Simulation Facility phase 1 has been finalized end 1994. The research facility is unique in offering capabilities such as high-performance motion and visual cueing together with a full- mission environment. The NSF is the world's first motion-based F-16 MLU simulator. The facility will not only offer extensive research and development possibilities for both Air Forces and

industry, but from an operational point of view, it will also be an asset in defining training (simulator) requirements.

During the 1995 time frame, the NSF will be extended to allow for advanced helicopter simulations. Based on high-fidelity simulation models, the intrinsic value of the simulator will increase dramatically. By virtue of designed and incorporated flexibility and modularity, the National Simulation Facility presents itself as an international testbed for advanced simulation possibilities.

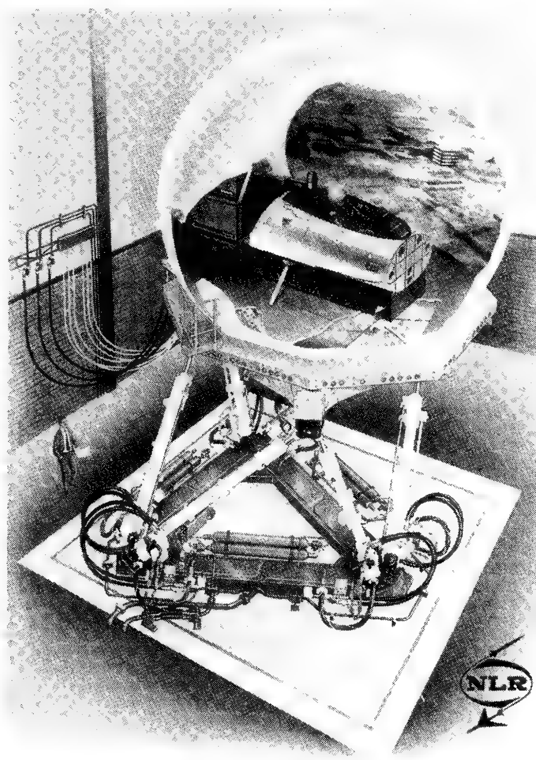

Fig.6: NSF cutaway drawing

The NSF will be extended towards simulation of two helicopters, recently procured by the Dutch Government, the Boeing CH-47D medium-heavy transport helicopter and the McDonnell Douglas AH-64D Apache attack helicopter.
The NSF wil support the Air Force in operating these helicopters, a new tactical and operational element to be used by the recently established Air Mobile Brigade, the Dutch rapid deployment force.

8. ABBREVIATIONS

ATC	Air Traffic Control
CEPA	Common European Priority Area
DIS	Distributed Interactive Simulation
EUCLID	European Cooperation for the Long term In Defence
FOV	Field Of View
HUD	Head-Up Display
I/O	Input/Output
IRIS	Integrated Raster Imaging System
ITEMS	Interactive Tactical Environment Management Simulation
LFWC	Lockheed Fort Worth Company
MFD	Multi Function Display
MLU	Mid Life Update
NLR	National Aerospace Laboratory
NSF	National Simulation Facility
OTW	Out-of-the-Window
RFS	Research Flight Simulator (of NLR)
RNLAF	Royal Netherlands Air Force
RTP	Research and Technology Project (EUCLID)
TCAS	Traffic-alert and Collision Avoidance System

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Simulateur multicible piloté pour le développement des conduites de tir air/air

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1. RESUME
La section Etudes et Simulation du Centre d'Essais en Vol (Ministère de la Défense) participe étroitement au développement des systèmes de navigation et d'armements (SNA) de tous les programmes d'aéronefs (Rafale, Tigre, Mirage 2000, ...).

Les essais en simulation de ces SNA nécessitent la mise en oeuvre de cibles ou d'équipiers reconstituant ainsi l'environnement tactique du pilote. Mais en fonction de l'état d'avancement des travaux, le besoin varie depuis un environnement tactique automatique jusqu'à la mise en oeuvre d'équipier ou de cibles pilotés pour un plus grand niveau de réalisme.

Ce premier besoin a entraîné le développement d'un simulateur complet capable non seulement de restituer l'environnement tactique en mode préprogrammé, mais aussi de simuler jusqu'à trois ou quatre aéronefs pilotés en assurant un parfait déterminisme et le contrôle de l'échange des données des SNA. Il était de plus nécessaire de pouvoir coupler ce moyen à chacun des simulateurs d'études de la section.

Le système appelé HEP ou Hostile/Equipier Piloté consiste en un calculateur central temps réel simulant deux ou trois aéronefs pilotés avec un SNA complet, jusqu'à 20 cibles air/air automatiques avec leur SNA lui aussi automatique et 100 menaces sol/air. Le cockpit des aéronefs pilotés est soit une cabine simplifiée avec toute la planche de bord sur un même grand écran tactile et un rétroprojecteur présentant l'image du monde extérieur, soit une mini-sphère COSMOS développée en coopération entre Thomson TTS et le CEV. Dans les deux cas, manche et manette proposent les vraies commandes temps réel. De plus, tous les SNA proviennent du portage des logiciels SNA de simulations d'études précédentes d'avions de combat, permettant ainsi un choix de plusieurs aéronefs réalistes et validés sans développement supplémentaire.

Le document présente le description détaillée du moyen, les premiers résultats de son utilisation en évaluation opérationnelle ainsi que les axes de développement ultérieur.

2. CONTEXTE
La Direction des Constructions Aéronautiques (DCAé) a concentré au sein du Centre d'Essais en Vol (CEV) l'ensemble des activités de simulation pilotée au profit du développement des grands programmes aéronautiques (Rafale, Tigre, Mirage 2000, ...).

Située sur la base d'essais d'Istres du CEV, au coeur des essais en vol de prototypes et d'intégration SNA aussi bien des avions d'armes que des hélicoptères, les missions de la section Etudes et Simulation sont :

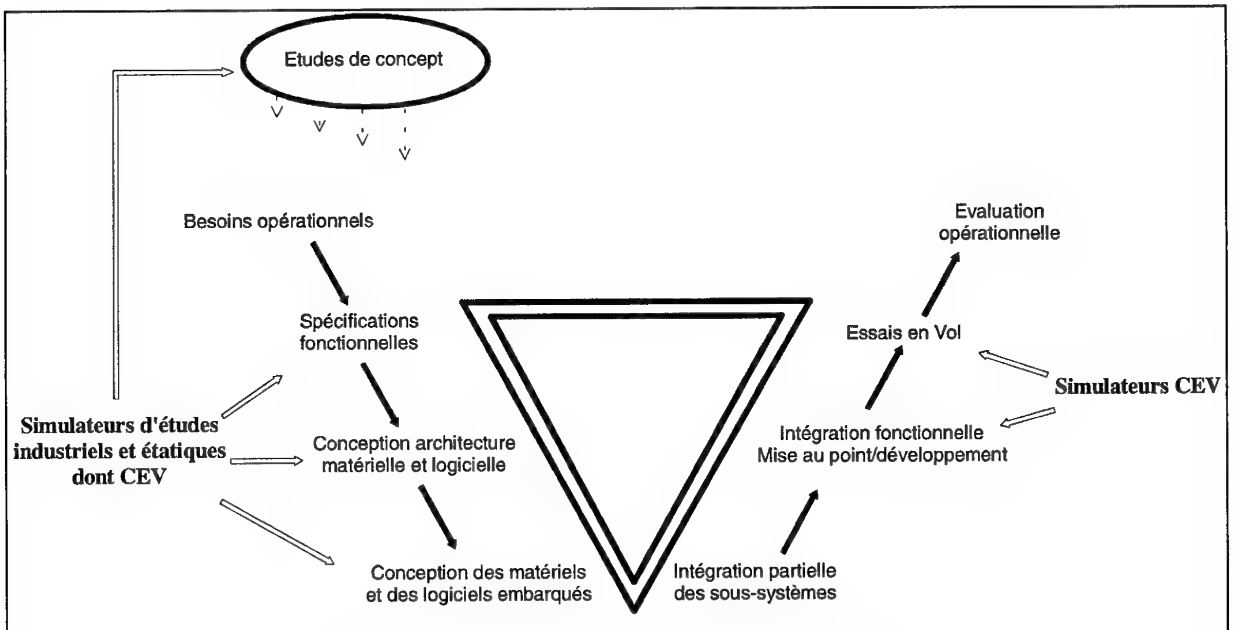

Figure 1 - la simulation dans les processus de développement

Paper presented at the AGARD FVP Symposium on "Flight Simulation — Where are the Challenges?", held in Braunschweig, Germany, from 22-25 May 1995, and published in CP-577.

a. étudier à moindre coût les concepts nouveaux, aussi bien dans les domaines de l'aviation civile que de l'aéronautique militaire,
b. fournir les éléments d'appréciation technique déterminant l'approbation ou les évolutions de spécifications nécessaires à l'adéquation des systèmes évalués aux besoins opérationnels,
c. analyser les situations à risque ou à charge de travail élevée,
d. rechercher les causes d'anomalies décelées en vol par rejeu à partir des données enregistrées en vol,
e. de former ou d'entraîner les équipages d'essais.

Ainsi, cette intervention de la section Etudes et Simulation du Centre d'essais en vol dans le processus de développement des programmes militaires et civils depuis les études de définition jusqu'aux évaluations opérationnelles des systèmes embarqués peut être résumée par le schéma de la figure 1.

3. BESOINS

3.1. Besoins fonctionnels

Les essais en simulation des systèmes d'armes multicibles nécessitent de mettre en oeuvre des scénarios composés d'un grand nombre de cibles ayant des comportements de plus en plus réalistes. Pour cela, l'animation des cibles peut être réalisée simultanément de deux façons distinctes :

- automatiquement par l'intermédiaire d'un logiciel de gestion des trajectoires, avec possibilité de contrôle par un opérateur unique. Ce logiciel est soit implanté sur le calculateur de simulation en étude, soit intégré à un gestionnaire d'environnement tactique sur station de travail dédiée à cette fonction,

- par pilotage des leaders respectifs des groupes de bombardiers ou d'escorteurs au moyen d'un simulateur simplifié piloté. Dans ce dernier cas, les trajectoires et le SNA des équipiers de ce leader piloté doivent être asservis automatiquement à celui-ci par le gestionnaire d'environnement tactique du paragraphe précédent.

Si le choix de scénarios automatiques est indispensable pour les phases de mise au point initiale d'une conduite de tir ou de familiarisation de l'équipage d'essais avec le nouveau système à évaluer, il est en revanche nécessaire de prendre en compte le comportement du pilote dans les cibles lors des évaluations opérationnelles et des phases de qualification du système d'armes.

Un deuxième grand besoin à couvrir est la capacité à restituer le contexte opérationnel du travail en patrouille. En effet, avions d'armes ou hélicoptères, rares sont les cas où l'aéronef travaille seul. Le plus souvent, le dispositif basique est la patrouille légère de deux avions, et il est essentiel de restituer la charge de travail liée à :

- la conduite de la patrouille, et la gestion de la cohérence de celle-ci,
- la répartition des objectifs à traiter au sein de celle-ci.

Ceci ne peut être assuré de manière réaliste que si deux équipages "humains" (et non préprogrammés) sont dans la boucle.

Enfin, il faut pouvoir mesurer les résultats obtenus et il faut que l'accoutumance au pilotage de ces cibles ou de cet équipier soit aussi faible que possible. Il est donc indispensable de faire appel pour ces simulations à des SNA bien identifiés et au comportement validé.

3.2. Besoins matériels

Cependant, si le réalisme du SNA doit être recherché, que ce soit pour un essai avec une patrouille homogène ou pour une patrouille hétérogène de deux aéronefs amenés à coopérer, il est souhaitable de pouvoir faire appel pour la simulation de cet équipier à une simulation légère au niveau de l'environnement matériel du pilote pour des raisons évidentes de coût d'une simulation d'études complète. Aussi bien pour l'environnement visuel que pour le cockpit lui-même, la mise en oeuvre de matériel économique était recherchée.

Il reste une contrainte à respecter au niveau des actions réflexes du pilote, le plus souvent effectuées à travers les commandes temps réel des manche et manette, en application du concept 3M (Mains sur Manche et Manette en français) ou HOTAS (Hand On Throttle And Stick en anglais). Cet environnement simplifié doit donc utiliser les manche et manette réels.

3.3. Autres besoins

D'autre part, des simulations pilotées simplifiées sont nécessaires pour :

- assurer des fonctions d'enseignement pour l'Ecole des Personnels Navigants d'Essais et de Réception (EPNER), ou de formation propres à la section Etudes et Simulation, là aussi avec un certain niveau de réalisme dans la simulation du SNA avec des concessions acceptables dans le domaine de l'environnement matériel, l'objectif étant une démonstration pédagogique et non une mesure ou une réelle évaluation de l'interface homme/machine,
- permettre de désactiver certaines chaînes d'études devenues trop onéreuses ou attribuées à d'autres essais tout en conservant la mémoire des essais effectués et des SNA validés.

4. ETUDES PRELIMINAIRES

Dans ce but, le Centre de simulation a développé ces dernières années un logiciel de gestion automatique des patrouilles et de l'environnement tactique, ainsi que plusieurs concepts de simulation simplifiée répondant à des objectifs bien définis.

4.1. Logiciels DALAI et ENVTAC

Le premier besoin présenté au paragraphe 3, la gestion automatique des trajectoires des cibles, a entraîné le développement du logiciel DALAI (Dispositif d'Animation des Logiques Aériennes d'Interception) par la section Etudes et Simulation. Une des caractéristiques les plus originales de ce logiciel est la gestion de la cohérence de la patrouille suivant des principes mis au point avec des pilotes opérationnels, en adaptant les évolutions au sein de celle-ci au type de formation retenue (formation de manoeuvre offensive FMO ou défensive FMD, patrouille serrée) et au facteur de charge de l'évolution. Ainsi suivant les cas, il peut y avoir croisement ou non au sein de la formation. Ce logiciel est capable de gérer plusieurs raids de bombardiers avec leurs escortes air/air ainsi que d'éventuels brouilleurs stand-off.

Très rapidement, il s'est avéré nécessaire d'ajouter à cette gestion des trajectoires des cibles air/air une simulation automatique de leur systèmes d'armes de façon d'une part d'exciter les contre-mesures de la simulation en essais mais aussi d'obliger le pilote de cette dernière à tenir compte des

capacités de tir adverse. Le logiciel DALAI s'est donc vu intégré au sein du logiciel ENVTAC (ENVironnement TACtique). Celui-ci est capable de simuler 20 menaces air/air et leur système, jusqu'à 100 menaces sol/air et 10 bateaux.

Au logiciel ENVTAC est associée une console de contrôle sur laquelle est présentée une situation 2D du scénario en cours ainsi qu'un poste de commande. Cette console est destinée au suivi du scénario, et à l'intervention sur les composantes non pilotées pour modifier le déroulement des scénarios préprogrammés, déclencher des évasives ou des manoeuvres de combat, activer/désactiver des menaces sol/air,... De plus, l'ingénieur dispose d'une image pseudo 3D vue depuis le cockpit d'un quelconque aéronef du dispositif voire d'un missile, présentant les paramètres essentiels et la position angulaire relative de tous les mobiles. Cela permet en particulier un suivi temps réel des tirs simulé et l'interprétation des comportements de sélection de cibles par l'autodirecteur.

4.2. Postes de pilotages simplifiés (PPS)

Le premier simulateur simplifié développé a été le concept PPS (Poste de Pilotage Simplifié). Il s'agit d'une cabine en bois reprenant les formes principales extérieures et intérieures du cockpit réel, dans lequel le pilote dispose des manches et manette réels ou au moins fonctionnellement identiques. L'ensemble de la planche de bord est regroupé au sein d'un grand écran tactile qui permet la sélection des différentes fonctions au SNA ne nécessitant pas une action réflexe du pilote. Le monde extérieur, dans lequel les réticules du collimateur tête haute sont directement incrustés, est présenté sur un rétroprojecteur placé devant la cabine.

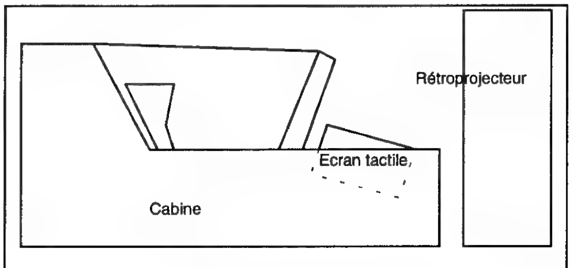

Figure 2 - Poste de pilotage simplifié

Ce concept de cockpit est particulièrement bien adapté pour un avion en mission air/sol en basse altitude où la prise en compte du relief est essentielle. En revanche, il ne permet pas les engagements air/air car le champ du rétroprojecteur de l'ordre de 40°*30° est trop limité pour les évolutions de combat.

Aujourd'hui, le CEV a développé deux types de cabines suivant ce concept, une monoplace et une biplace.

4.3. Mini sphères COSMOS

Pour les essais à dominante combat air/air, le CEV et Thomson TTS ont développé le concept de minisphère COSMOS de seulement 2 mètres de diamètre, qui permet de disposer d'une présentation omni directionnelle de cibles générées par deux projecteurs laser. Le pilote dispose d'un horizon de 180° de champ obtenu par un projecteur fish-eye et d'une symbologie tête haute directement présentée sur la surface de la sphère par un troisième projecteur. Le fait de disposer d'un projecteur spécifique pour cette dernière est essentiel car il permet de garantir une bonne résolution à cette projection sous forme d'une image télévision alors que ce type de figuration est habituellement généré par des tubes à balayage cavalier.

Enfin, des tests pour l'ajout d'une fenêtre frontale d'une image du monde extérieur ont été réalisés et semblent prometteurs.

4.4. Enseignements et limitations

Ces premiers développements ont été effectués sur des structures informatiques indépendantes, stations de travail pour le PPS et les logiciels DALAI et ENVTAC, châssis VME spécifique pour le COSMOS. Si les concepts ont donnés satisfaction, d'importantes limitations sont vite apparues. Les premiers enseignements sont donc les suivants :

- le logiciel ENVTAC répond aux besoins d'essais et ses capacités en nombre de menaces sont suffisantes pour la complexité des scénarios à traiter. Les outils de préparation de scénarios en temps différé et le poste de contrôle en temps réel nécessitent certes un apprentissage mais sont d'une convivialité suffisante. Enfin, la présentation 2D du dispositif associée à la vue cockpit lorsque cela est nécessaire permet une interprétation aisée de la situation. Il n'y a donc pas de besoin de recherche complémentaire pour une présentation 3D plus complexe.
- le premier PPS disposait d'un logiciel SNA simplifié. Cela posait des problèmes de mise en oeuvre par les pilotes qui ne retrouvaient pas un avion aux fonctions connues. Cela a confirmé la nécessité de simuler des SNA réels et validés.
- la multiplication des structures temps réel posait des problèmes de mise en oeuvre (lancement non centralisé) et de synchronisation. Le non déterminisme des échanges à travers des liaisons Ethernet et de la structure temps réel même des PPS entraînaient la multiplication de modules de datation et d'interpolation dont la validation fonctionnelle posait quelques problèmes en ce qui concerne les conduites de tir missiles et la guerre électronique.
- la multiplication des structures posait des problèmes de maintenance, aussi bien des systèmes informatiques que des logiciels applicatifs modélisant les SNA et les symbologies associées, et entraînait des surcoûts matériels.

5. SPECIFICATIONS SYSTEME

Un groupe de travail interne à la Section a été créé avec pour objectif de définir une architecture informatique capable de fédérer l'ensemble de ces simulations simplifiées, désormais baptisées HEP soit Hostile/Equipier Piloté, et l'environnement tactique automatique complémentaire.

Tout d'abord, la réalisation d'essais multi-cibles et/ou multi-aéronefs impose, en raison de la nécessaire capacité à interpréter les résultats obtenus :

- le déterminisme de toutes les composantes en jeu et des couplages entre ces différentes composantes, à savoir qu'à iso conditions initiales, les phénomènes observés sont identiques, en particulier non pollués par des processus propres au calculateur et externes à l'objet simulé (délais, retards, ...),
- la réalisation de rejeux et d'enregistrements.

En conséquence, il faut mettre en oeuvre une liaison déterministe à haut débit entre la simulation d'études et la structure HEP, ou entre les différents éléments du HEP, à base de mémoire réfléchie ou partagée.

Deuxième nécessité, la mise en oeuvre de SNA bien connus, réels et validés impose, afin d'éviter des surcoûts de développement, de réutiliser des logiciels issus des simulations d'études précédemment utilisées, ce qui permet de limiter les opérations de création de nouveaux hostiles ou équipiers pilotés au seul portage de logiciels des simulations d'études vers la simulation HEP. Il est donc indispensable de respecter des normes strictes aussi bien au niveau de la structure d'accueil que des développements des logiciels de façon à minimiser les temps de portage.

La nécessité d'une maintenance simple impose une même structure temps réel aussi bien pour les PPS, les COSMOS que l'ENVTAC. L'analyse des coûts conduit alors à un compromis : une grosse machine est plus économique que plusieurs petites liées par mémoire réfléchie, mais est moins souple d'emploi principalement en terme de modularité. En fonction de la complexité des essais visés opposée à la nécessité de pouvoir les maîtriser et les exploiter, le choix s'est porté vers une structure capable de mettre en oeuvre 2 aéronefs pilotés au sein de l'environnement tactique automatique plus une simulation simplifiée autonome (instructions ou étude légère).

Dans le même esprit de simplification des opérations de maintenance et d'évolutivité, il a été décidé d'uniformiser le principe d'un grand écran tactile simulant la planche de bord identique pour les PPS et les COSMOS, en utilisant pour la génération de cette planche de bord graphique le même progiciel.

Ainsi, le schéma de principe de HEP est le suivant :

écran tactile (2 dans le cas d'un biplace) et soit une station de travail générant le monde extérieur et les réticules tête haute incrustés dans le cas d'un PPS, soit la mini sphère COSMOS avec sa baie VME qui assure les asservissements de projecteurs, les générations de cibles et de la symbologie tête haute.

6. ARCHITECTURE RETENUE

6.1. Généralités

Le but de ce chapitre est de décrire les grands principes de l'organisation fonctionnelle du système HEP, qui ont présidé à la réalisation de la structure d'accueil temps réel.

L'ensemble est basé sur la répartition des modèles en deux classes : les *modèles critiques* et les *modèles non critiques*. Par modèle, on entend un module logiciel qui simule le comportement d'une plate-forme ou d'un de ses équipements, ou une fonction (ou partie de fonction) de son SNA. Par exemple, ce peut être le modèle radar, le modèle pilote automatique, le modèle symbologie tête haute, le modèle sons et alarmes...

Un modèle critique produit des données qui doivent être fournies avec des contraintes temps réel à d'autres modèles qui les consommeront : par exemple, les données issues d'un des radars sont des entrées des contre-mesures des autres SNA, etc. Pour un modèle non critique, un retard induira peut être une légère perturbation, mais ne remettra pas en cause la *cohérence* de l'ensemble. Dans l'exemple précédent, un retard de quelques 3 ms pourra suffire pour que les contre-mesures des autres systèmes ne travaillent pas au cycle suivant sur les dernières

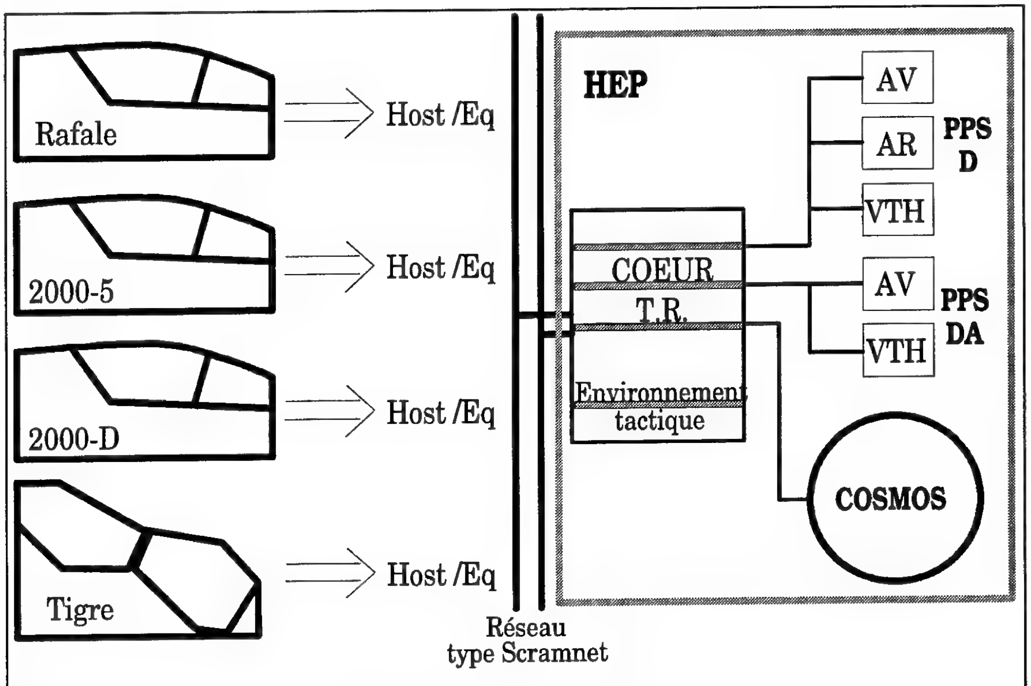

Figure 3 - Principe général HEP

Le coeur temps réel HEP peut à être couplé à chacune des simulations d'études (rafale, 2000-5, TIGRE, ...) par mémoire réfléchie. Chaque objet au sein du système HEP, telle une cible ou un équipier pilotée occupe un processeur auquel est couplé par liaison Ethernet le matériel nécessaire à la simulation du cockpit : la station de travail générant la planche de bord sous

informations radar. Ceci pourra aller jusqu'à retravailler sur les données identiques à celles du cycle précédent. Le fonctionnement des SNA en sera donc perturbé. En revanche, un même retard de 3 ms sur la production des réticules de pilotage ne sera pas perçu par le pilote, qui est pourtant en boucle fermée sur la simulation. La génération des figurations

tête haute, et plus généralement de l'ensemble de l'IHS (Interface Homme Système, ou MMI, Man Machine Interface en anglais) est donc paradoxalement non critique au sens HEP.

6.2. Description fonctionnelle d'un HEP

Décrivons maintenant un Hostile ou Equipier Piloté donné, tel qu'il est résumé par la figure 4.

Dans le cas d'un HEP couplé à une simulation d'étude et éventuellement d'autres HEP, trois mécanismes sont mis en jeu : un mécanisme de contrôle et de synchronisation en provenance de la simulation maître, un mécanisme d'échange de données avec les autres constituants de l'essai, et un mécanisme de configuration de l'ensemble du système HEP.

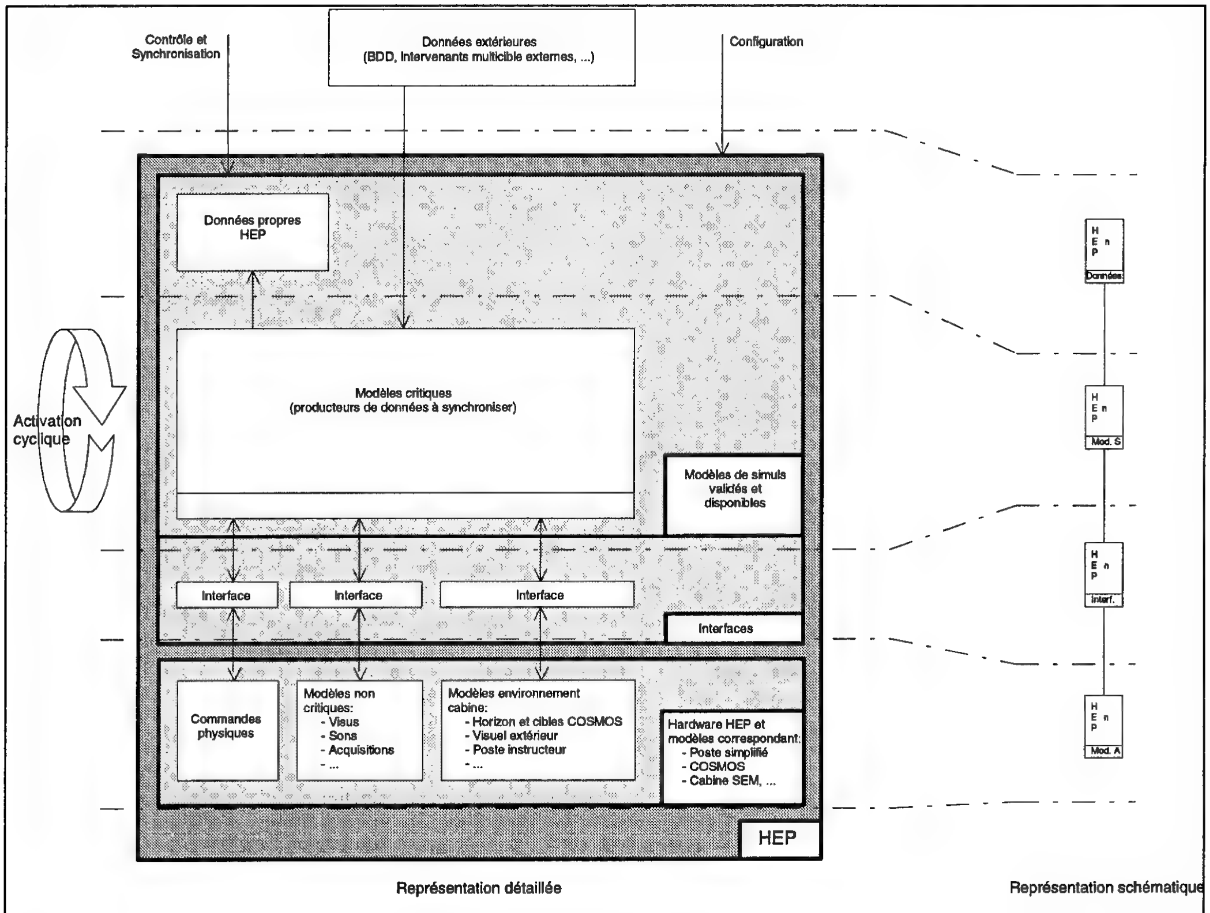

Figure 4 - Description fonctionnelle d'un HEP

Il est constitué :

- de modèles critiques, simulant le comportement d'un aéronef piloté (plate-forme, capteurs, conduites de tir,...) ; ces modèles sont activés cycliquement,
- d'interfaces de couplages entre les modèles critiques et les moyens d'environnement faisant partie des HEP ; ces moyens sont constitués, pour un HEP donné :
  . d'une cabine ou d'une mini sphère COSMOS constituant le poste de pilotage duquel sortent les commandes physiques, notamment celle utilisée pour le pilotage proprement dit,
  . de modèles d'environnement cabine permettant de présenter au pilote un visuel extérieur, un horizon, des cibles , et à l'instructeur son poste de travail,
  . de modèles non critiques présentant au pilote (et à l'instructeur le cas échéant) des figurations, des signaux sonores, etc. ou faisant l'acquisition de données cabine (par exemple un poste de commandes de système d'armes).
- de structures de données propres au HEP considéré manipulées par les divers modèles.

6.3. Cas particulier de l'ENVTAC

Du point de vue fonctionnel, l'environnement tactique est un HEP comme un autre. La figure 5 ci-après résume la modélisation. La différence réside dans l'environnement propre de ce HEP qui n'a pas de cabine, et dans le fait qu'une console spécifique est mise à disposition de l'ingénieur d'essais en salle d'écoute et de conduite d'essais.

6.4. Description fonctionnelle du système HEP complet

La figure 6 présente le système HEP complet dans son fonctionnement multicible et autonome. On distingue :

- le simulateur d'études utilisant le mécanisme d'échange de données avec les HEP (production et consommation), le mécanisme de contrôle et de synchronisation, le mécanisme de configuration des HEP,
- la salle d'essais comprenant le poste ingénieur d'essais et le poste environnement tactique,
- la gestion du système HEP : administration, développement, gestion de la configuration du système,
- la plate-forme HEP support des HEP individuels dans leur ensemble, fournissant les services de mise en oeuvre

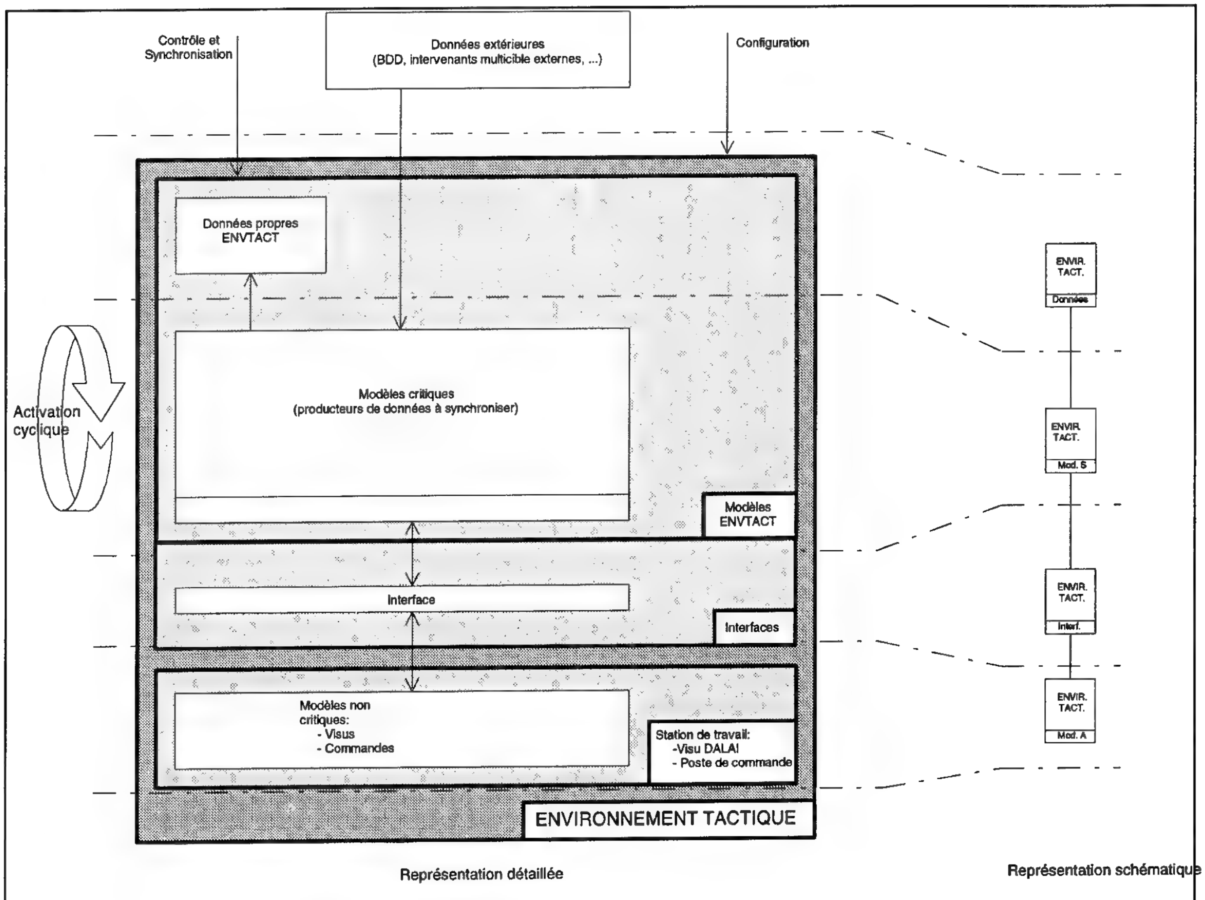

Figure 5 - Description fonctionnelle de l'Environnement Tactique

opérationnelle (couplé ou autonome) et de fonctionnement global en multicible couplé,
- l'ensemble des environnements propres à chaque HEP.

Lorsque le système HEP est couplé à une simulation d'études, pour des essais multicibles ou simplement pour la simulation d'un équipier piloté, c'est le calculateur de la simulation d'étude qui est le calculateur maître de la simulation globale.

Coeur de la plate-forme HEP, la structure d'accueil gère les couches *données, modèles synchrones* (critiques et cycliques) et *interfaces* des HEP. Elle ne gère pas les environnements propres à chaque HEP. Elle fournit les services suivant :

- initialisation et activation des modèles correspondant à la configuration des HEP choisie, en multicible ou en autonome,
- synchronisation entre HEP participant à un même essai en ce qui concerne les données et l'activation des tâches synchrones critiques (modèles et interfaces),
- synchronisation des HEP participant à un essai multicibles avec le simulateur d'étude impliqué ; ceci concerne les échanges de données, et le contrôle de l'activation des tâches synchrones,
- dialogue avec les machines supportant les modèles asynchrones (symbologies par exemple) ; ce dialogue pourra être de type synchrone ou asynchrone, critique ou non critique suivant les cas.

7. PREMIERE CONFIGURATION D'ESSAIS

7.1. HEP prototype

Deux raisons principales ont conduit à la réalisation d'un prototype. D'une part, il fallait valider l'ensemble des principes retenus, matériels, informatiques et applicatifs sur un objectif de taille raisonnable. D'autre part, il est dangereux dans tout projet informatique de fixer des objectifs trop lointains.

L'objectif de ce prototype est donc le suivant : un système HEP comprenant un environnement tactique automatique, au sein duquel deux Mirage 2000 DA peuvent être pilotés, l'un en cabine PPS et l'autre en COSMOS. Le système HEP doit être couplé à la simulation RAFALE.

De plus, un HEP autonome doit pouvoir être activé indépendamment de l'utilisation ou non du reste en mode couplé, à des fins d'instructions ou de démonstration. Il doit s'agir soit d'un Mirage 2000 DA, soit d'un hélicoptère de transport.

En ce qui concerne les services implémentés dans la structure d'accueil, l'essentiel des grandes fonctions demandées est disponible. Le détail est décrit en annexe. En revanche, l'étude d'un point important, à savoir la capacité de disposer de deux HEP couplés à deux essais indépendants, fera partie d'une phase ultérieure.

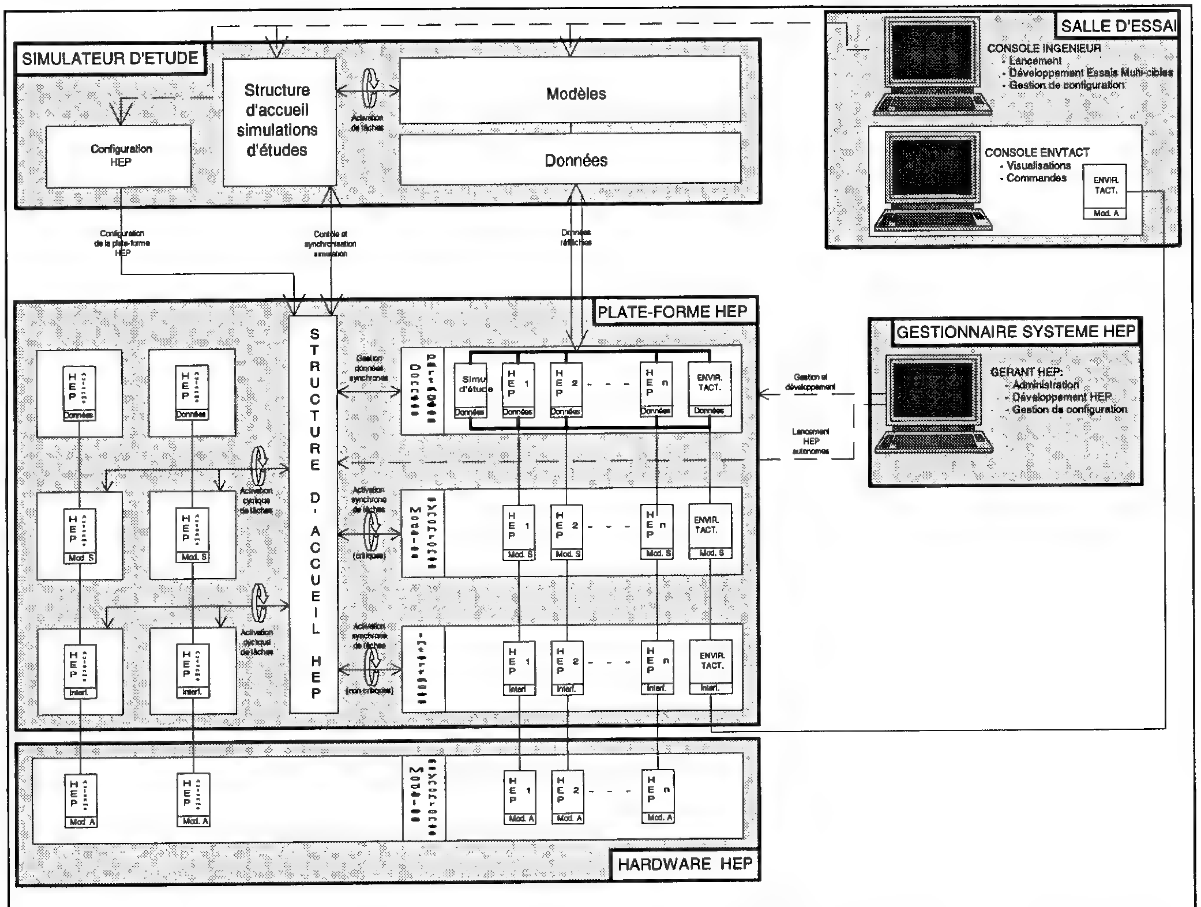

Figure 6 - Description fonctionnelle du système HEP

Le choix de deux simulations simplifiées Mirage 2000 DA, l'une en cabine PPS et l'autre sur COSMOS, répond à plusieurs raisons. Tout d'abord, le Mirage 2000 DA est un avion bien connu des ingénieurs de la section et le SNA est, pour les critères d'aujourd'hui, relativement simple. Cela présente donc l'avantage de limiter les aléas de portage (même s'il en existera toujours).

En même temps, il s'agit d'un avion bien connu des pilotes du CEV et de l'Armée de l'Air, ce qui facilite la prise en main du simulateur et permet de pouvoir porter l'accent sur la validation des concepts de cette simulation simplifiée, sans rencontrer de problèmes sur l'applicatif. Il sera ainsi possible de conclure sur les capacités et les limitations respectives du PPS et du COSMOS, ce qui n'aurait pas été le cas si les aéronefs simulés avaient été différents. En particulier, une grande partie des interceptions se passe aujourd'hui à proximité du sol, et, en l'absence (provisoire) d'image du monde extérieur dans le COSMOS, le moyen le plus adapté en fonction des essais envisagés sur la simulation d'études ne pouvait pas être tranché.

Limiter le nombre de HEP pilotés à 2 correspond aussi à un souci de souplesse de mise en oeuvre. La composante pilotée n'a d'intérêt que si elle est mise en oeuvre par des pilotes formés à l'emploi des conduites de tir simulées ou similaires. Sinon, le caractère réaliste et opérationnel disparaît et il vaut mieux revenir à des scénarios automatiques validés avec des opérationnels.

Enfin, il s'agit d'un objectif de minimisation des travaux nécessaires à la réalisation et la validation de ce prototype. En particulier, l'arrivée du second COSMOS n'était prévu qu'au début 95, ce qui n'autorisait pas un délai suffisant pour une utilisation en essais.

D'autre part, les premiers résultats concernant l'environnement tactique (paragraphe 3) ayant montré que le produit était satisfaisant, il a suffi de redécouper le logiciel ENVTAC suivant la décomposition fonctionnelle présentée au paragraphe 6.3.

7.2. Configuration HEP prototype

La configuration matériel pour le coeur temps réel retenue est un calculateur Harris Night Hawk 5836.

Pour la mémoire réfléchie entre ce calculateur et la chaîne de simulation d'études, le choix s'est porté sur un SCRAMNET™ LX de la société Systran. Il permet en particulier une certaine souplesse sur la distance entre les calculateurs, ce qui est appréciable dans un bâtiment où les salles de calcul sont assez éloignées l'une de l'autre, lorsque le système pourra être couplé à tous les simulateurs du centre.

Pour la génération des planches de bord sous écran tactile, le progiciel graphique VAPS™ de la société VPI a été retenu, en raison de l'expérience déjà acquise par la section sur ce produit. Il présente certes l'inconvénient de demander des puissances de calcul relativement importantes si l'on veut conserver une fréquence de rafraîchissement des images suffisante mais

permet une reconfiguration aisée des planches de bord en fonction des besoins.

7.3. Configuration de l'essai RAFALE/HEP

Un des points majeurs de l'essai sur le simulateur RAFALE était l'évaluation des conduites de tir air/air et du combat à proximité du sol. La cabine de simulation est donc pour cela placée dans une sphère de projection qui présente deux cibles générées par des stations de travail sur toute la surface de la sphère et une image frontale du monde extérieur sur un champ de 130°×35° générée par une machine 3 canaux VISA4 de Thomson TTS. Naturellement, un traitement logiciel permet de sélectionner au sein de l'environnement tactique les deux cibles prioritaires qui seront prises en compte par les générateurs de cibles et les projecteurs spécifiques correspondants, en privilégiant les aéronefs pilotés par les deux HEP, les autres mobiles étant présentés par la machine VISA4, mais de ce fait limités à la fenêtre frontale.

En raison des objectifs de l'essai, deux points ont demandé une validation particulièrement soignée :

- les interactions radar de l'un avec les contre-mesures des autres et ce dans les deux sens de façon à ne pas déséquilibrer les rapports de force. Sur ce point, la maîtrise des échanges de données et la synchronisation des structures temps réel du RAFALE et des HEP sont des éléments essentiels à la crédibilité et au réalisme des scénarios.
- l'intervisibilité entre les différents mobiles, et donc la prise en compte d'une base de données de terrain (BDD) commune au système dans son ensemble.

Ce dernier point mérite quelques précisions car la cohérence des BDD de terrains est un élément critique à toute simulation interactive distribuée. Il faut non seulement disposer en au moins un endroit de l'ensemble d'un module calculant l'intervisibilité de tous les mobiles actifs, pilotés ou non, et des menaces sol/air au sein de l'environnement tactique, mais il faut aussi distribuer cette information sur tous les systèmes d'armes. Là encore, la synchronisation des structures temps réel et la maîtrise des échanges de données par mémoire réfléchie a été un atout considérable. Dans le cas présent, c'est l'environnement tactique qui dispose d'une copie de la BBD et calcule ces intervisibilités.

Il faut aussi assurer un visuel du monde extérieur cohérent pour tous les aéronefs qui en disposent, c'est-à-dire dans le cas présent le simulateur RAFALE et le HEP en cabine PPS (le COSMOS devant en disposer dans un prochain développement, voir paragraphe 3.3). Pour des raisons de coût, le PPS ne dispose que d'un visuel bas de gamme sur stations de travail, mais la cohérence altimétrique est assurée par la reprise d'une BDD ayant une altimétrie identique à celles de la VISA4 du RAFALE et de l'environnement tactique. Ce visuel dispose pour plus de réalisme de motifs de phototexture. Enfin, des objectifs reconnaissables similaires ont été placés aux mêmes coordonnées sur cette BDD et la BDD VISA4.

8. ENSEIGNEMENT - DEVELOPPEMENT ULTERIEUR

8.1. Enseignements

L'évaluation en simulation pilotée du premier standard utilisateur du RAFALE a constitué la première utilisation opérationnelle de la plate-forme HEP, dans la configuration décrite au § 7.3. Ces essais étant aujourd'hui achevés, il est possible de dresser un premier bilan de cette utilisation.

L'apport de la plate-forme HEP réside principalement dans le réalisme accru qu'elle a conféré à la simulation, et, par voie de conséquence, à la qualité et à la force des conclusions de l'essai.

L'amélioration constatée, par rapport aux moyens d'environnement multicibles de la génération précédente (DALAI), se situe à deux niveaux :

- d'une part les manoeuvres effectuées par les "mobiles HEP" sont plus représentatives (niveau élémentaire),
- d'autre part les scénarios sont globalement plus réalistes (niveau macroscopique).

Le niveau élémentaire s'explique par la qualité du modèle avion simulé sur HEP, qui est sans commune mesure avec un modèle simplifié de cible, associée au fait qu'il y a réellement un pilote aux commandes. Grâce à cette amélioration des qualités manoeuvrières des cibles, les modes et commandes spécifiques au combat de l'avion en étude ont pu être évalués avec une dynamique très proche de celle d'un combat aérien réel, et, de plus, multicible.

Le niveau macroscopique découle inévitablement du premier, mais y participent également :

- l'existence de systèmes d'armes hostiles ou amis très complets interagissant avec celui de l'avion en essai,
- la possibilité de simuler une mission avec un équipier réel et les aléas que cela comporte,
- l'impact psychologique non négligeable qu'engendre sur les pilotes évaluateurs, la présence d'un ou plusieurs autres intervenants humains dans la mission simulée, et qui se traduit par une motivation et une agressivité accrues. Ce point est très important : en effet, cette interactivité entre plusieurs pilotes contribuent à faire *oublier le simulateur*, donc à renforcer la crédibilité des résultats et leur transposition vers un cadre réel.

Tous ces points ont concouru à augmenter la charge de travail du pilote jusqu'à un degré comparable à celui rencontré lors d'une mission de combat.

Il convient de revenir sur la coexistence de simulations de systèmes d'armes complets, rendue possible par le concept HEP. Elle a permis durant l'évaluation pilotée du RAFALE, d'obtenir un contexte d'interaction entre avions du point de vue de leurs radars, armements et contre-mesures respectifs d'une richesse inégalée. C'est dans ce domaine, on le verra plus loin, que s'ouvrent les perspectives essentielles de développement des HEP.

Les deux types d'interface différents (cabine PPS et mini-sphère COSMOS) se sont révélés être complémentaires. La cabine PPS a été plutôt utilisée dans le cas d'avions censés ne pas engager le combat à vue, bombardiers par exemple, alors que la mini-sphère COSMOS a été attribuée à des aéronefs dont la mission était, a contrario, l'escorte ou l'interception, que ce soit en tant qu'hostile ou en tant qu'équipier du RAFALE. Dans ce premier essai, la capacité à travailler sur une image du même terrain que l'avion en étude s'est révélée être un atout significatif de la cabine PPS. Ceci était en particulier le cas lorsque le profil de la mission simulée donnait une grande importance relative aux phases en basse altitude : il a alors été parfois préféré de limiter

le rôle du HEP au travail au delà du visuel des cibles (BVR en anglais) et de faire l'impasse sur la capacité à engager le combat à vue.

8.2. Développements ultérieurs

8.2.1. Généralités
Ce premier essai a démontré tout le potentiel du HEP dans le domaine de l'interaction entre les systèmes d'armes puisqu'il permet d'intégrer n'importe quelle simulation existante et, par là même, d'adapter le contexte en fonction des thèmes d'étude (air/air, air/sol, air/surface etc.). On peut également envisager, au-delà des études de développement, des simulations multi-HEP destinées à parfaire les tactiques d'emploi des systèmes d'armes embarqués. La seule limitation à ces développements réside dans le fait qu'il faut assurer une cohérence suffisante entre le niveau de représentativité de la modélisation des différentes simulations mises en oeuvre, or celles-ci pouvant ne pas avoir été conçues pour interagir avec un environnement aussi riche, il conviendra de les adapter voire de les enrichir afin d'utiliser pleinement les possibilités offertes par le concept HEP.

8.2.2. Environnement tactique
Le principe lui-même de l'ENVTAC ne devrait que peu évoluer. En revanche, les capacités devraient augmenter en terme de fonctionnalités pour l'utilisateur, de fonctions simulées et de nombre d'entités. L'évolution la plus notable au niveau des fonctions va être l'introduction d'un simulateur de réseau MIDS dont les spécifications sont en cours d'élaboration.

En ce qui concerne le nombre de menaces, la situation actuelle permet déjà des scénarios complexes. Cependant, pour plus de souplesse dans la définition des scénarios, le nombre de mobiles air/air va augmenter de façon à disposer d'un contexte aérien important pendant toute la durée de missions longues.

Un autre axe de développement à court terme est l'introduction d'un module de combat automatique du type de ceux déjà utilisés dans certains simulateurs d'entraînement opérationnels. Le principal intérêt est de gérer une patrouille d'escorte de manière entièrement automatique avec une qualité acceptable par rapport à un aéronef piloté, en permettant de concentrer les deux COSMOS maintenant disponibles à la simulation d'une autre escorte homogène.

8.2.3. Aéronefs simulés
Dès maintenant, le développement d'un aéronef capable de mission air/sol tout temps est en cours. Il s'agit de la reconfiguration de l'actuel PPS 2000D au standard HEP. Lorsqu'il sera opérationnel, cela permettra de disposer d'un dispositif de raid adverse constitué d'une patrouille de bombardiers en très basse altitude, capable de suivi de terrain automatique, accompagné de deux escortes air/air dont tous les leaders de patrouille sont pilotés, leurs équipiers ayant des trajectoires automatiquement asservis à celui du leader. Le leader de la patrouille de bombardier 2000D utilisera la cabine PPS biplace, les deux leaders des escortes pilotant les deux COSMOS.

La transposition des autres simulations d'études actuellement disponibles à la section Etudes et Simulation vers la plate-forme HEP suivra ensuite en fonction des besoins des essais en cours.

8.2.4. Moyens d'environnement
Les cockpits "bas coûts" utilisés ont donné entière satisfaction. En particulier, la mise en oeuvre de commandes temps réel réalistes permet une accoutumance très rapide du pilote à cet environnement simplifié, l'activation des fonctions à travers l'écran tactile n'interférant pas avec les phases à forte charge de travail.

En revanche, des développements sont dès maintenant en cours pour équiper les cabines COSMOS d'une capacité de visuel frontal du monde extérieur. Cela permettra ainsi de couvrir tout le domaine d'utilisation depuis le vol basse altitude jusqu'à l'engagement du combat à vue.

Ultérieurement, il pourrait être intéressant d'augmenter le nombre de mobiles aériens projetés dans les COSMOS.

8.2.5. Système HEP
Plusieurs évolutions du système HEP sont envisagées à plus long terme. Parmi celles-ci citons le développement d'une capacité de couplage DIS, qui permettrait un intéressant élargissement du champ d'action et d'expérience comparés de ces deux concepts d'interactivité aux objectifs très différents.

9. CONCLUSION
En résumé, revenons à la question fondamentale : pourquoi HEP a-t-il été développé ? Il s'agissait, pour évaluer finement le comportement d'un système d'armes dans un environnement réaliste, de créer un réseau local faisant interagir un nombre *limité* d'aéronefs *pilotés*, typiquement inférieur à 8, au sein d'un environnement tactique complexe et varié.

Il fallait donc créer, sans contrainte de récupération d'architecture existante, une structure permettant d'établir et de maîtriser le dialogue et donc les interactions entre plusieurs modèles de systèmes d'armes. Le problème est donc inverse de celui posé par DIS, où plusieurs simulateurs existants, pouvant être très éloignés les uns des autres et de caractère parfois très hétérogène, doivent interagir.

Aujourd'hui, HEP répond, dès sa version prototype, parfaitement au problème posé et permet d'assurer un haut niveau de réalisme des engagements aériens, avec un souci de minimisation des coûts de l'environnement matériel en fonction des besoins des pilotes grâce à trois types de cockpit : cabine d'étude complète pour l'essai proprement dit, mini-sphère COSMOS ou poste de pilotage simplifié.

Le champ d'application de HEP apparaît très vaste, pour toute application locale demandant le réalisme de la modélisation globale et la capacité d'analyse des phénomènes rencontrés :

- élaboration des tactiques d'emplois des nouveaux systèmes embarqués,
- études de concept amont dans le domaine n contre p afin de valider les orientations de développement des systèmes futurs.

Les outils sont là pour garantir le réalisme des comportements relatifs des différents intervenants, à condition que le niveau de représentativité des modèles soit suffisant. Paradoxalement c'est la structure informatique, frein classique à l'affinage des modèles informatiques, qui, dans ce cas précis, motivera une mise à niveau de la modélisation.

ANNEXE A
Planches de description du concept COSMOS.

ANNEXE A

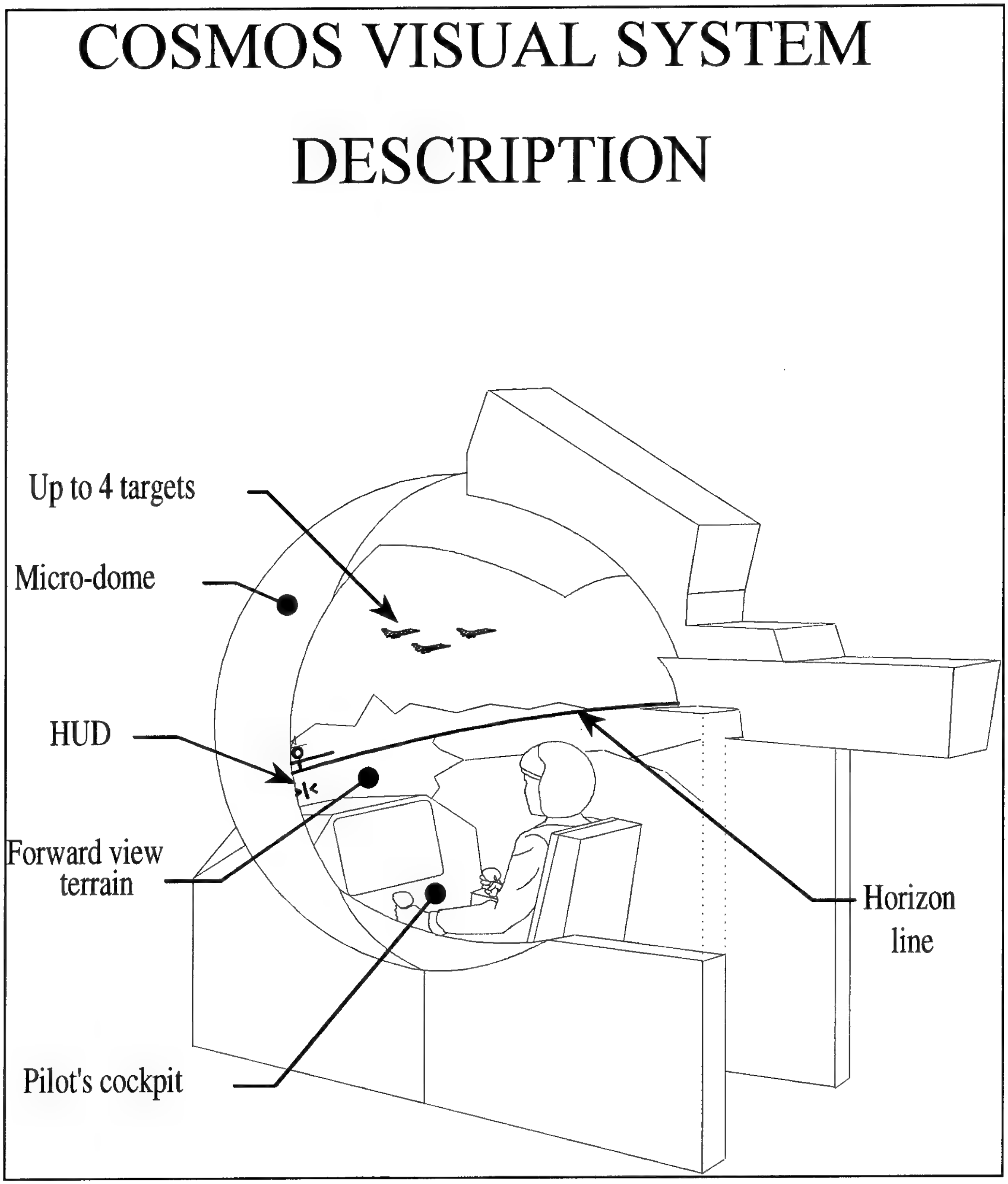

Figure 1 : Description de la cabine COSMOS

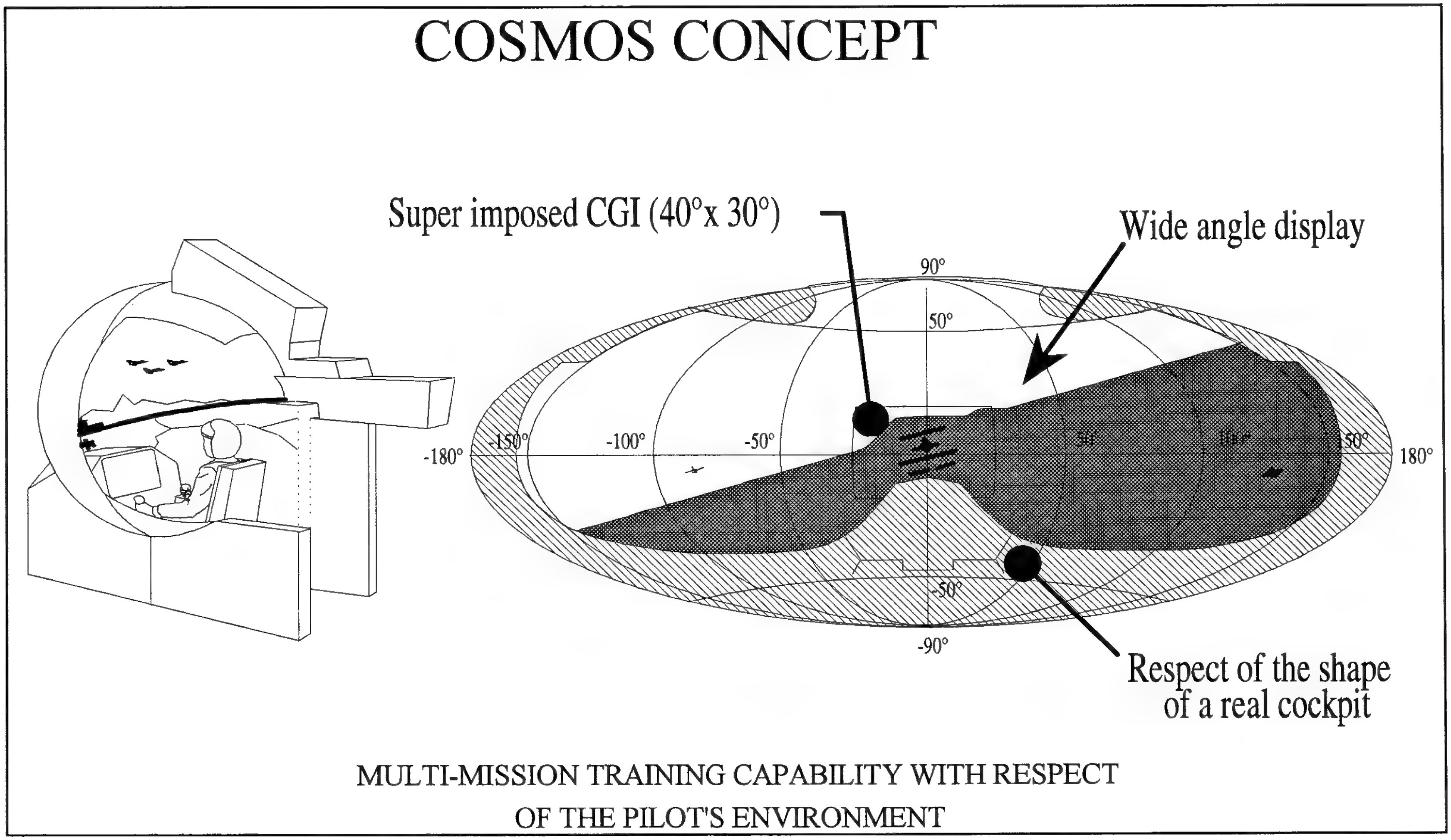

Figure 2 : Epure de visibilité de COSMOS

Issues in the development of training analysis methodologies

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SUMMARY

Training analysis is a topic that is often talked about and less often carried out. Various methods have been proposed in the past, but many of these have been too complex and too prescriptive for practical purposes. Major system procurements on cost-plus contracts in the past may have justified detailed methodologies, but the majority of modern training analysis is required on small fixed price contracts. The training analyst is often solely responsible for the work, or working in a small group of 2 or 3. Consequently, the analyst has to use techniques that can be easily applied and be flexible enough to carry over from one contract to another.
This paper describes a range of issues that affect training analysis and presents a simple methodology that can be easily adopted by analysts and applied to commercial situations.

1. INTRODUCTION

Consider the following situations:
- An air force is introducing a new aircraft type.
- An army faces an increasing number of low-intensity, multinational operations.
- Naval personnel with experience using mechanical equipment find that their jobs have changed and they now have to operate electronic equipment.
- Office workers find themselves surrounded by computer technology that they are unable to use effectively because they don't understand it.
- The boss of an engineering firm says that many people seeking work do not have the skills for the jobs available.

Each of these situations will be improved by training. Therefore we can say that they all have 'training needs'. It is not always easy to define the best solution to any set of training needs. It is often the case that the person who identifies the problem has also instinctively identified a solution. However, the first solution proposed may not be the best one. This is because the problems expressed above are multi-dimensional and there are many different ways of addressing each of them. The methods of 'training needs analysis' or 'training analysis' provide a systematic way of examining problems such that training solutions can be based on a credible process.

The scope of training analysis is extremely wide and this has led to the term sometimes being used inappropriately. This paper describes some of the issues that are involved in training analysis so that no matter what particular methodology is used, the sponsor of the analysis should be able to recognise the key elements.

2. MYTHS OF TRAINING

(After references 1 and 2)

2.1 Myth: practice is training.

There are several forms to this myth, for example an over-reliance on experience rather than training 'I don't need courses, I have done this job for years'. Even those designing training programmes can fall into the trap: 'sit by Nellie' or 'job shadow', are both popular techniques that rely on the theory that observing practice and taking part constitutes training. A more successful approach is to decompose the job into tasks that require specific skills and to train the individual skills separately before combining them. Consequently, learning to fly an aircraft is separated into psychomotor skills such as manouvering, landing etc, procedural skills such as checks, and cognitive skills such as navigation.

Practice is important for a range of reasons including: confidence building, providing a transition from training to working, embedding skills and knowledge, providing a period where errors can be tolerated, etc. However, simply carrying out mock tasks is not necessarily useful and may serve to demotivate trainees since they are unlikely to perform well.

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It is important for the development of staff skills that the correct balance is made between practice and training. In the military context, practice (exercises) involves a large number of people. Some people may be required to carry out undemanding tasks to support the exercise. It is important to try and maximise the training benefit for as many people as possible. The larger the scale of the exercise, the more difficult the problem becomes.

2.2 Myth: Training requires realism

The reasons that realism is regarded so highly include:

- training programme designers sometimes do not know what are the important cues for a task so they want to have them all just in case they miss one;
- realistic training is so hard to achieve that it acquires a high status associated with expensive solutions;
- subtask training is sometimes difficult and trainees would often prefer to progress to the real task.

The whole of the simulation industry is based on providing analogues of the real world. The demand for high quality representation of the real world (fidelity) has provided a driver for sophisticated devices. In some areas, fidelity is simple to provide (e.g. cockpit switches), in other areas it is extremely difficult (e.g. high resolution daytime images). The never ending demand for better fidelity makes it easy to confuse simulator fidelity with simulator effectiveness. In any case, fidelity is much easier to measure than training effect.

The important issue for training programme design is that the correct cues are available to support the task being trained. An air combat simulator may have a requirement for high resolution visual detail on target aircraft but very little on the home aerodrome. Conversely a civil aircraft simulator will need very little detail on other aircraft and very high resolution on the home aerodrome.

It is of course, very difficult to assess what is the minimum cue required for training effect on any task. Indeed, most simulators are required for a variety of tasks so it is tempting to specify the highest possible cue fidelity. However, it is essential to remember that demanding realism will not necessarily provide good training.

2.3 Complex tasks require complex training solutions

Since aircraft are very complex pieces of machinery with complex tasks, there is often the assumption that the training also needs to be complex. The budgets for training are high enough to buy complex training devices. However, some complex training can easily be carried out in a classroom. For example, team tasks tend to be very complicated social interactions, yet some useful skills can be learnt with simple training aids. It is not necessary to equate the task complexity or the system complexity with the complexity of the training solution.

2.4 Expert users know how to train

Training requires specialist skills. These skills are not necessarily the same as those in other jobs. Whilst expert users are sometimes very good trainers, it is a mistake to believe that this is always the case or that the experts need little additional training or support for developing the specialist skills they need to pass their expertise onto others.

2.5 Myth: stressful training is good training

Novices sometimes find that the process of learning new skills is stressful. This is often because several skills have to be adopted at once. For example, flying aircraft circuits requires many skills e.g. manual tracking tasks, procedural tasks such as conducting checks, perceptual tasks such as searching the ground, airspace and instruments, communication tasks such as making radio calls and handling radio calls as they come in, etc. All of these activities have to be carried out in real-time and the novice has to devote conscious attention to many of them. This is why the novice feels overloaded when the expert does not. Most of these lower level skills have behavioural components e.g. speaking on the radio, where performance is easily assessed, and stress is apparent e.g. in voice pitch.

With strategic tasks activities such as time planning are more important determinants of performance than behavioural skills. This makes performance less easy to assess and stress becomes less apparent. The trainee working moderately hard may appear to be calm. This calm exterior can lead an instructor to believe that no training is taking place, the temptation is therefore to add extra tasks into the training session until trainee stress becomes visible.

2.6 Myth: training that was good for me will be good for others

This myth arises from resistance to change if an alternative training strategy is proposed. It also

comes about from the following logic: I can do the job. A trainee wants to do the job. Therefore the trainee wants to be like me. Therefore the trainee must repeat the training that I had.

The initial training programme encountered by the skilled operator may well have been designed 25 years ago. This may have been supplemented by additional training or experience over many years. The new trainee will have an entirely different background and will be familiar with interacting with people and technology in a different way. Therefore it is important that training programmes should be updated to take these factors into account.

2.7 Training analysis is great, but I don't need methods. I can use my own judgement and common sense.

Since everybody is human, everybody has some expertise in human science. We have all experienced training, and it is likely that we have all experienced both good and bad training. Therefore instinctive and common sense opinions on training are worth listening to. However, common sense can be wrong, e.g. it gave us the flat earth theory.

3. TRAINING ANALYSIS METHOD

There are a variety of methods that are proposed for the analysis of training. Ultimately, the objective of training analysis is usually to design new training programmes. For this reason, many training analysis methods are called Instructional Systems Development (ISD) models. According to sources in Reference 3, there are over 60 ISD models. One of these models is the Interservices Procedures for Instructional Systems Development (IPISD) which has led to a military standard (Mil Std 1379D).

All such models are tools to assist the practitioner and it is the emphasis on achieving the objective of good training systems that is important. Each training analysis has different requirements and therefore a method has to be specific to the application, or sufficiently generic to be applied across a range of domains. In the case of generic methods, Mil Std 1379 has a problem for practitioners because it is too prescriptive to be used in acquisition programmes that are greatly divided up into individual fixed price subcontracts.

What has been found to be useful in Thomson Training & Simulation is a model that is generic and less prescriptive so that it can be adapted to the commercial environment. This is under continuing development, but the diagram below illustrates the model.

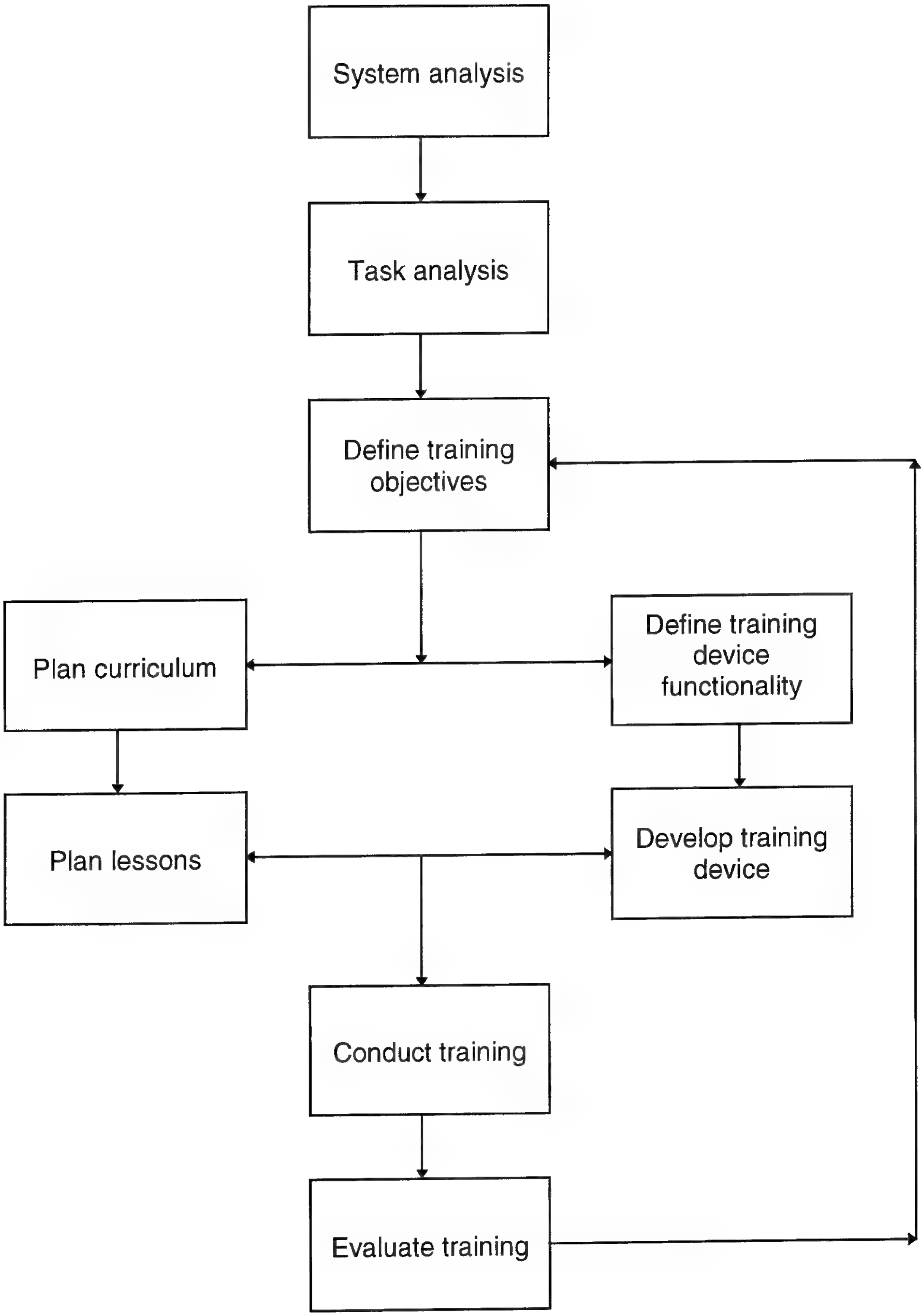

Figure 1. A simple training analysis method

4. DATA SOURCES

4.1 Contract

Contractual obligations have to be met regardless of whether there is training value in the activity. Sometimes the analysis may highlight a mismatch between contractual requirements and training needs. If it is a serious problem, the analyst may have to draw the attention of the customer to the mismatch. This will allow the customer to make a modification to the contract.

In most cases, contractual requirements impose little extra workload for the analysis.

4.2 Customer input

Customer satisfaction is important to commercial organisations. Therefore if a customer has a preference for a system configuration or feature, then that is what they will get. In training system design it is important to acknowledge that the customer will have an influence.

It is also important to note that the customer is not usually the end user. The person or people responsible for contract specification, award and acceptance can be quite different types of people from the instructors and trainees, indeed some of them may be in a different domain e.g. administration rather than aviation.

There may also be people within the customer organisation who have expertise about training system development that can be valuable to the training analysis. Good management of the customer/producer relationship can produce a higher quality analysis.

4.3 Standards

There are various military and civil standards that may be complied with. For example, Mil Std 1379D. Standards are often difficult to work with, may contradict each other and may have been superseded by current knowledge. However, if a contract requires compliance with standards then they will affect the training system.

4.4 Authorities

Authorities can influence the training system either by the production of standards or by other means such as certification of the equipment.

4.5 Equipment manufacturers

Simulators have to replicate the appearance and the functionality of equipment in the target system. This means that very specific details are required by a simulator manufacturer. In a commercial environment where the equipment manufacturer is competing with the simulator manufacturer, data transfer becomes a very important issue.

Equipment manufacturers should have information about equipment design philosophy which is extremely important to understanding training requirements.

4.6 Predecessor systems

Some training systems have to be designed even before the target equipment is in service. This is quite understandable since users need to be trained before they use the equipment. However, this presents real problems for training analysis since the level of user knowledge about the system is likely to be extremely low, possibly only available from test users operating prototypes.

A common way of dealing with this problem is to extract data from users of existing systems performing the same or similar functions.

4.7 Courseware

Most training system design occurs as part of a development of existing systems. Therefore there are usually documents such as curriculums and training manuals. In some cases, all that is needed is an update of the existing courseware, in other cases, there will need to be a reconfiguration of the whole system. As an early step in the analysis, it is essential to ensure that the courseware is obtained and examined.

4.8 Subject Matter Experts

Training analysis depends on having information about the task. Some of this information may be known by designers and some of it may be available in other documentation. However, most training analysis work requires direct access to users for task knowledge elicitation. Since the system is designed for human use, it is clear that the users should be involved in the design process.

It often surprises those attempting to conduct training analyses how difficult it is to obtain user involvement in system design. One way to make user involvement easier is to have Subject Matter Experts (SMEs) as user representatives. One definition of SMEs is that they will satisfy the following criteria:

- Appropriate qualification. If the task to be trained is flying a Tornado, then the person should be qualified to fly that aircraft.

- Task knowledge. They should have task knowledge. If the task is multi-aircraft tactics, then the person should know how to carry out that task.
- Expertise. They should be good at the task.
- Currency. Their expertise should be current. In complex socio-technological systems such as an air force, tasks change very rapidly. Sometimes information that is only one year old can be incorrect.

These requirements are quite difficult to achieve, but it is important to strive for the ideal. If access to SMEs is not possible, then non-SMEs may be used as long as their limitations are acknowledged. It is sometimes a problem with training analysis that somebody is made available to the study and declared to be an SME when they do not match the above requirements. This is a particular problem in aviation where there are lots of enthusiasts who have some limited knowledge of the domain.

4.11 Research

A lot of work is being done in research centres on training. This research changes the thinking about how training needs can best be met. It also changes thinking about methodologies.

Close links with research organisations can help provide an effective analysis.

4.12 Observation

Documents can be quite specific about what happens in any job, and SMEs can also give details about what happens. However, it has been demonstrated on many occasions that what people say happens and what actually happens are two separate things. Therefore it is important to observe tasks whenever possible. The observer will obtain vital information about the task that would be unavailable otherwise. It is often the most important information that cannot be reported verbally or in writing since it sometimes can involve users doing what they may think is not allowed.

5. TASK FOCUS

5.1 Sophistication.

Tasks can be relatively simple, such as learning how to use a word processor or they can be complex such as learning how to deal with aircraft malfunctions. In the former case, the task is accessible to the analyst but the latter is so sophisticated, it is almost impossible for a training analyst to have complete awareness. This affects how the analysis is conducted.

5.2 Safety.

Some systems have safety as a priority. Examples are nuclear power stations and civil aircraft. This biases training towards error reduction.

5.3 Performance.

Military fast jet training prioritises performance and the time domain becomes more critical.

Ease of use.

Civil systems such as cars, ticket machines, and office equipment tend to focus on ease of use. Modern computerised equipment is now expected to be operated without any specialised or dedicated training at all. The training therefore needs to be reduced to a minimum or embedded within the operation of the equipment.

Scope.

It is important that the scope of the task is defined. The training analysis can only examine a range of tasks and the scope of the tasks has to be defined. Scope definition prevents the analysis from being drawn outwards. For example, scope can define a start point as being qualified to operate the aircraft and an end point as being qualified to carry out a given range of missions successfully.

6. SYSTEM FOCUS

6.1 Technology.

Complex training devices are produced by engineering organisations where the system focus is quite natural on technology. Cost is a technology factor which affects training analysis, it is now possible for the analyst to consider computer based training since the costs have reduced radically in recent years. Feasibility is another technology factor which affects training. For example, high resolution visual displays representing daylight terrain and airports can now be suggested on simulators.

Something that meant training on real aircraft is now feasible in a simulator. The training need has not changed, only the technology.

6.2 People.

Systems involve people as well as technology. This is often forgotten, probably because so much effort is expended getting the technology to work. The focus of the analysis is on the whole system and that means that a lot of effort needs to be spent looking at the people issues. This is why user involvement is so important.

7. USER FOCUS

7.1 Stakeholders.

In any training development programme there is usually a range of people who have a legitimate interest in the system. These can be called stakeholders. There will be what are usually called end users. So a word processor or an aircraft may have end-user i.e. those people who have their hand on the controls. However, if we consider that most jobs serve other people we can consider the end users as primary e.g. the secretary or the pilot, and we can also consider secondary users such as a manager or the passengers who are directly affected by the performance of the primary user. There may also be various tertiary users such as the company or airline staff.

In addition to users there are other stakeholders. Maintenance staff have an interest in training programme development. Often their needs are not considered until late in the analysis process. System designers have an interest since they have to work with limited resources and may be recalled to modify a system. Complex and unique solutions may meet the training needs, but they may be difficult for device designers to produce.

A Target Audience Description is a useful document to produce as part of the training analysis. This contains a list of the types of people will be trained and their characteristics. This can be agreed with the customer, and the very process of producing the document helps extract useful user information.

7.3 Range of jobs.

Many training systems are used for a range of jobs. A simulator may be used by a pilot, a copilot, an engineer, cabin crew etc. Although the explicit demand for training may be for one job, the facilities may usefully provide training for several jobs. Relatively slight modifications to the training devices procured as a result of the analysis can help training for the other jobs.

7.4 Range of experience.

There will be a range of experience in system users from trainee to test pilot. There may be the person who is trying to obtain remedial training to retain a job. This person will want simple clear training systems with tactful handling of mistakes. There may be the expert instructor with combat experience who relishes challenging situations and needs to explore the limits of an aircraft envelope.

7.6 Team stability.

Teams may be stable because they often work together and may even live together, as in the military. They may be unstable so that they may have less awareness of what to expect from each other, as in civil airlines. Stability will affect team interactions and this affects how people should be trained. Crew Resource Management is a recent initiative in the airline industry which addresses the training needs of this issue.

7.7 Trainee or instructor.

Training systems have to meet the needs of trainees, but they also have to meet the needs of instructors. As training devices get more complex and options increase, instructors face an increasing workload. The system should enable instructors to produce interesting and challenging training with minimum effort which allows them to concentrate on trainee activity.

7.8 Future proofing.

Training system development is a time consuming and expensive business. Solutions should ensure that there is some future proofing built into the system. Thus if a modification to the real world system is made, then the training programme can be updated relatively simply.

7.9 Credibility

There may be some features of training that are done more for user credibility than for training effect. Examples include: having a particular lesson with the real equipment rather than in a simulator, enhancing simulator fit to include extra controls and displays, making the training devices look attractive. These features may not affect training directly, but they may have an indirect effect. The trainee that believes that

training system works well is likely to be more receptive to the training.

8. TRAINING EFFECT

- Changing people. Courses of training or sessions using a simulator must be used to change people. Many people experience the compulsary course where attendance is all that is required and no real difference is made to the trainee. The training programme should be designed around the objective of producing a change in people rather than just spending course time on a range of topics.
- Directed. Training must also be directed. We can change people, but it must be in ways that we want. Programmes need to be developed to ensure that the training objectives are achieved.
- Effective. Training has to be effective. Thus the benefit must be in terms of task performance, operational (and training) costs, safety, or operator satisfaction. It is often difficult to measure training effect but we should still try to make sure that training systems are designed for effect.

9. CONCLUSIONS

Training analysis has been shown to have many influencing factors. These have been described with suggested way of dealing with them. Various popular myths about training have been described with explanations as to why they are incorrect. A simple method has been shown which is simple and flexible enough to cope with the limited scope, resources and timescale of the modern contract.

10. REFERENCES

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Delayed Pilot Response in Windshear

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Abstract

Windshear can cause fatal accidents. To pass windshear situations safely, the automatic flight control should be employed. This advice is in contrast to an FAA recommendation to switch off the autopilot in a windshear and to perform a go-around procedure.
With conventional instrumentation and manual approach extremely large time delays up to 40 seconds could be identified. It is still unclear what the psychological reasons for this delay are. There are some indications that the human being reacts like a band pass filter. With proper display information a thrust command director can be realized that may force the pilot to react correctly and safely in windshear situations.

List of symbols

F	thrust
H	height
t	time
u_{W_g}	horizontal wind component
w_{W_g}	vertical wind component
V	airspeed
V_K	flight path velocity
V_W	wind speed
W	weight
x, x_g	distance/flight path
γ	flight path angle

1. Introduction

Several fatal accidents, especially those caused by windshear finish with an undesired ground contact of the aircraft approximately one nautical mile prior to the runway threshold (fig. 1). The aircraft attitude is sufficient, the rate of descent is moderate, but the ground is not prepared for an aircraft touchdown. This can be observed especially when the aircraft is flown manually. A comparison with fully automatic approaches under the same conditions show a delayed throttle response caused by the pilot. The delay time of pilots is more or less correlated with the cycle time of the aircraft phugoid motion and is in the order of 30 seconds. There is still no sufficient physiological explanation for this enormous time delay. In this paper some simulation results are presented to evaluate this time-delay effect. The selected windshear type is a low level jet, best suitable to produce clear results.

2. Low Level Jet

The term "low level jet" is used to describe wind phenomena of the lower part of the boundary layer, characterizing jet like wind profiles with a low altitude wind maximum. This kind of wind profiles has been observed in connection with specific local terrains, thermal effects in mountain valley regions, frontal activities, and the nocturnal boundary layer. Usually the nocturnal low level jet appears in the time between late afternoon and dawn under clear nocturnal sky when a strong radiation temperature inversion develops. Because of the strong stability in the inversion layer friction disappears and the unbalanced Coriolis and pressure gradient forces produce an acceleration of wind speed. Reference [1] describes the evolution of low level jets as a nonstationary process where the vector difference

[1] Since February 1995 Flight Operations Inspector / Flight Simulators at the Federal Civil Aviation Administration (LBA)

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between the actual wind and the geostrophic wind is rotating nearly circularly around the geostrophic wind (inertial oscillation), see fig. 2.

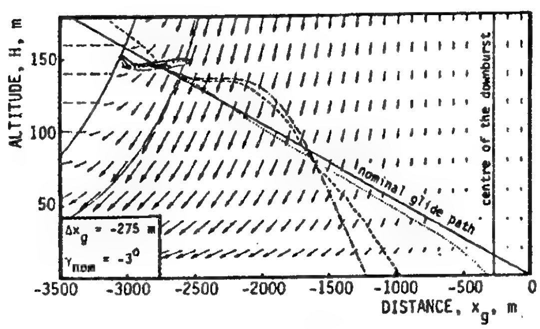


Figure 1: Landing approach through a downburst
-.- fixed controls
.... autopilot (no autothrottle)
--- reconstructed flight path of an accident occured in New York on June 24, 1975

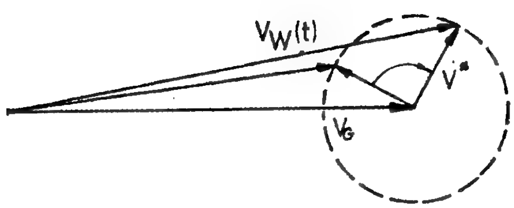


Figure 2: Inertial oscillation of wind vector

In the northern part of Germany the low level jet can be found approximately in 10 percent of all nights. Hence, a lot of data has been collected in the last years by means of tower and aircraft measurement [3, 4, 5]. Fig. 3 shows a typical low level jet sample recorded during a windshear measuring project by means of an Airbus A 300 operated by Lufthansa. A wind maximum of the 1.8-fold value of geostrophic wind speed and the 4.5-fold value of reference speed (H_{ref} = 10 m) was observed as well as a change of wind direction of about 90 degrees in a vertical layer of 300 m height. Investigations in the plains of northern Germany carried out on two meteorological towers of 300 m height [5] show a cycle period of 14,5 hours for the inertial oscillation. During take-off and landing approach the critical zone of windshear is passed in only one or two minutes. In this case the temporal evolution is not relevant and modeling can concentrate on quasi-stationary engineering models. Velocity profiles like low level jet wind profiles have been observed in fluid dynamic research of free jet and wall jet. As a first low level jet approximation a superposition of a boundary layer profile (for instance the power law) and a plane free jet velocity profile is used (see fig. 4). Measured data and equations for the free jet have been published among others by [6] and [7].

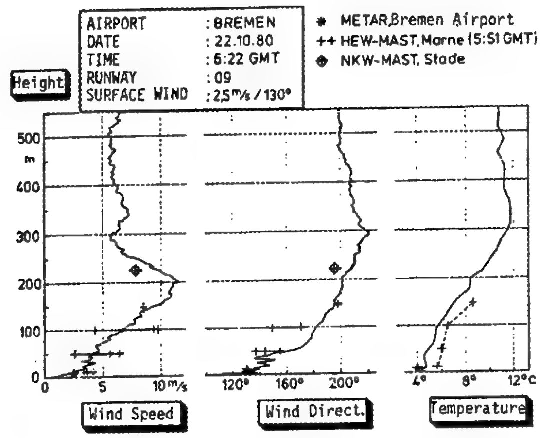


Figure 3: Low level jet measured in-flight

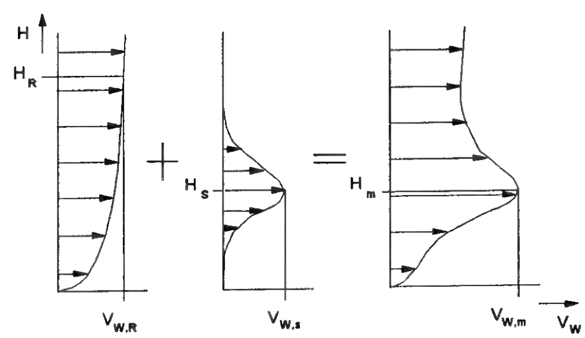


Figure 4: Composition of the low level jet model

For a large number of data records a comparison of measured data with modeled low level jet has been carried out. The examples of tower data (fig. 5) and aircraft data (fig. 6) are in good agreement with the model.

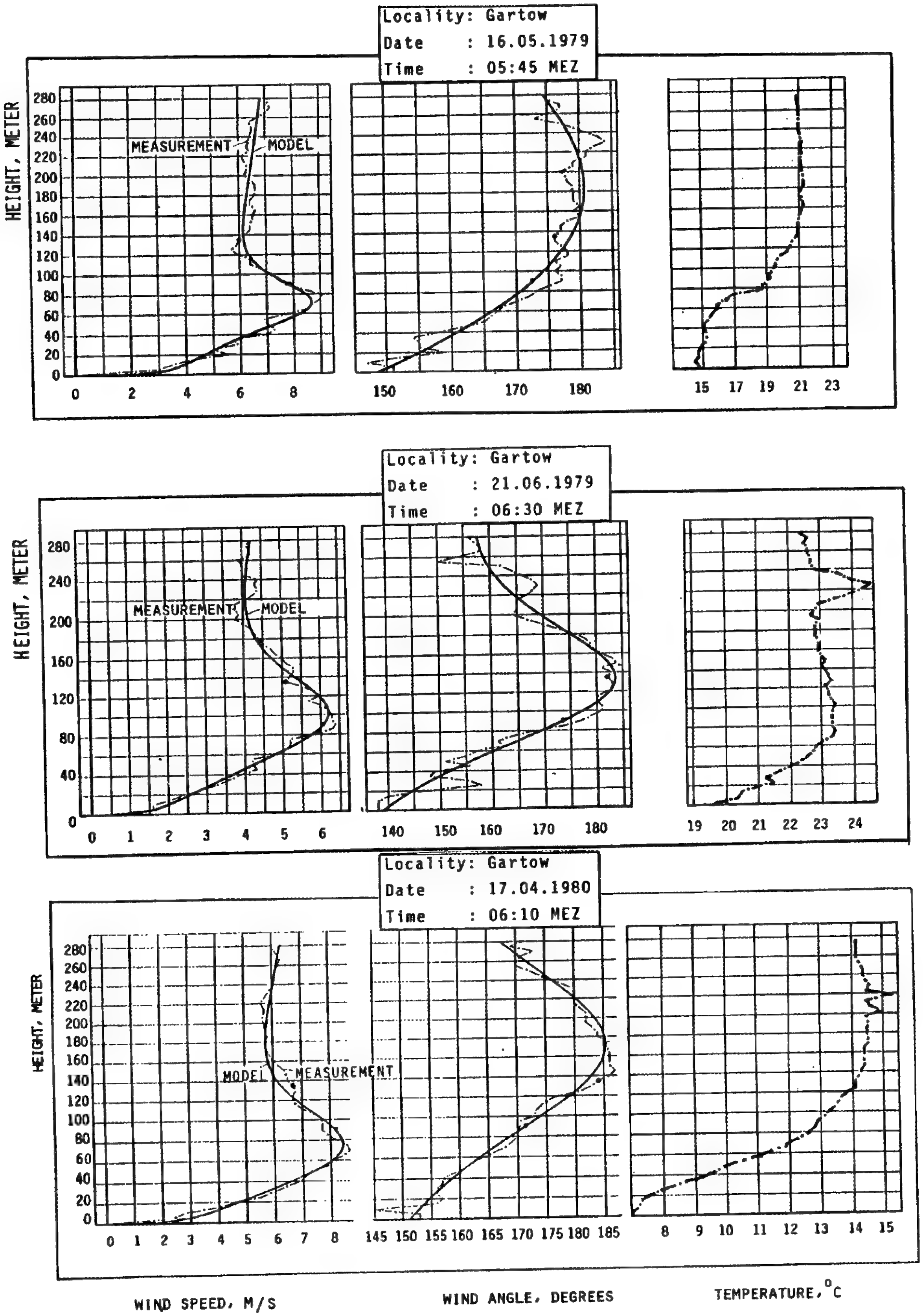


Figure 5: Approximation of tower data

Worst case profiles for the low level jet have been approximated from Soviet measurements (fig. 7) [8].

A typical feature of low level jets is the extremely low degree of turbulence as a consequence of the stable atmospheric conditions. This fact is important for the simulation results, as pilots cannot identify the windshear simulation through a correlated turbulence. This is in contrast to the typical downburst, where high windshear gradients, high downdrafts and extreme turbulence are correlated.

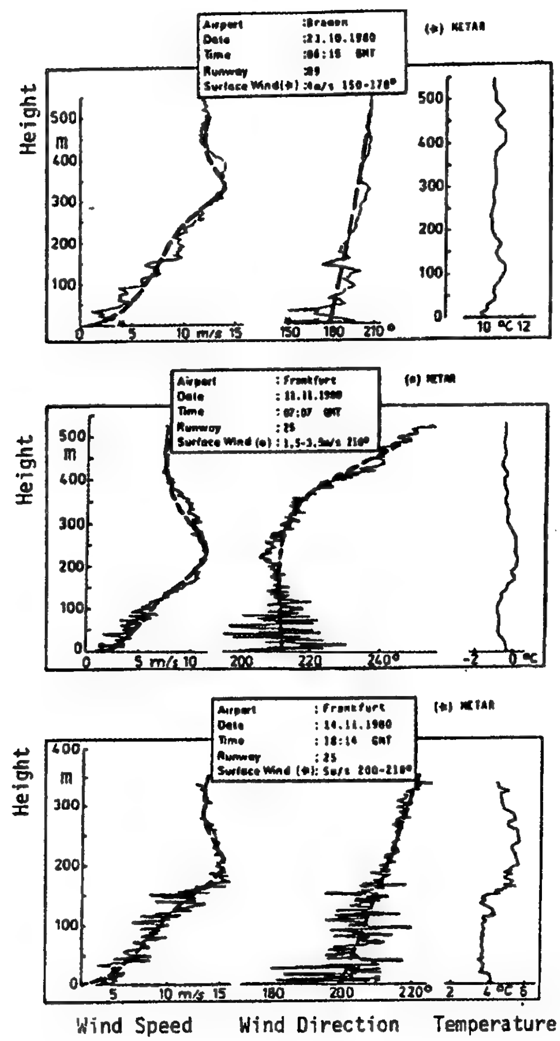


Figure 6: Approximation of flight data

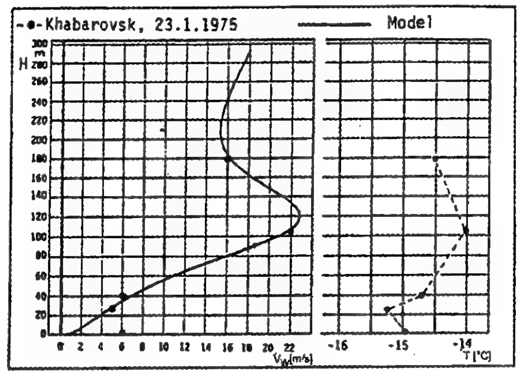


Figure 7: Approximation of a worst case profile

In all cases the maximum windshear gradient u_{WH} is greater than 0.2 s^{-1} according to the ICAO's definition (table 1).

intensity of windshear	influence on the flight path	variations of wind speed within $\Delta H = 30$ m	u_{WH} [s^{-1}]
low	neglectable	0 - 2 m/s	0.0 - 0.07
moderate	significant	2 - 4 m/s	0.07 - 0.13
strong	heavy	4 - 6 m/s	0.13 - 0.20
very strong	dangerous	> 6 m/s	> 0.20

Table 1: Classification of vertical windshear gradients (ICAO) [9].

Such a windshear may be defined as dangerous. In contrast to this definition, in most flight measurements no pilot comments were reported and no significant deviation of flight path and airspeed were obtained. Only the extremely low level jet of Khabarovsk (fig. 7) caused a fatal accident.
Based on these reported low level jet measurements a set of four windshear profiles were generalized for simulator campaigns to evaluate the pilot response in such windshears.

3. Simulators and Pilots

Two different types of simulators have been used for the tests:

- Airbus A 340 full flight simulator, designed and produced by CAE and operated by the Berlin Center for Flight and Simulation. This simulator can be operated in two modes:

  a) as a certified training simulator
  b) as a research simulator

- Fixed base simulator of a turboprop powered aircraft. This simulator is based on an

original Metro II cockpit including instrumentation. It was designed and is operated by the Braunschweig Technical University, Institute of Flight Guidance and Control. The copilot's control panel was modified to take up a programmable Electronic Flight Instrument System (EFIS).

In total 8 airline pilots and 6 test pilots, all of them very experienced, performed 86 evaluable approaches.

4. Simulator Results

A simulated approach through the Khabarovsk low level windshear is shown in fig. 8. After passing the wind maximum in a height of 120 meters, the decreasing headwind moves the aircraft below the glide path. The pilot initiated a go around manoeuvre and could survive, but the height above ground was of only a few meters. A small building or a tree would have caused a fatal accident (approximately 1200 meters before the nominal touch down point). The small airspeed variation is remarkable. The approaches of 14 pilots were very similar.

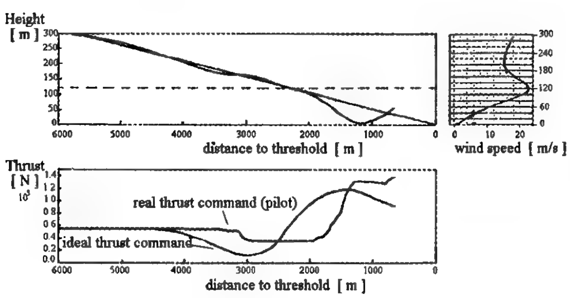


Figure 8: Approach through a low level jet

The ideal thrust control law of eq. (6) has been used as a reference system in the simulations and it will be implemented in the Institute's research aircraft DO 128. The principle of throttle control is based on fundamental flight mechanical equations [12]. As the flight path velocity (inertial velocity) V_K is the sum of airspeed V and wind speed V_W, the respective accelerations (time derivatives) are

$$(1) \qquad \dot{V}_K = \dot{V} + \dot{V}_W$$

The driving force is the wind acceleration as function of the windshear gradient dV_W/x

$$(2) \qquad \dot{V}_W = \frac{dV_W}{dx} \cdot \frac{dx}{dt} = \frac{dV_W}{dx} \cdot V_K$$

With an ideal flight control system, the airspeed has to be constant and therefore $\dot{V} = 0$. This results in

$$(3) \qquad \dot{V}_K = \dot{V}_W = \frac{dV_W}{dx} V_K$$

In the ideal situation (V = const.) the aircraft has to be accelerated with the wind variation. Equation (3) is a differential equation with its inherent dynamical characters.

The required thrust of an aircraft normalized with its weight W is

$$(4) \; \Delta\frac{F}{W} = \dot{V}_K + \Delta\gamma + \frac{w_{W_g}}{V}\cos\gamma + \frac{u_{W_g}}{V}\sin\gamma$$

If the flight path is maintained constant the flight path angle deviation $\Delta\gamma$ has to be zero. With a neglecting vertical wind component and small flight path angles w_{W_g} we get

$$(5) \qquad \Delta\frac{F}{W} = \dot{V}_K + \frac{u_{W_g}}{V}\gamma$$

If the airspeed is constant ($\dot{V} = 0$) we obtain the thrust control law by introducing eq. (3) into eq. (5):

$$(6) \qquad \Delta\frac{F}{W} = \frac{dV_W}{dx} V_K$$

If we multiply eq. (6) by the speed V_K we get the specific excess power:

$$(7) \qquad SEP = \dot{H}_E = \frac{dV_W}{dx} V_K^2$$

The energy variation expressed as energy height (or total energy) is

$$(8) \qquad H_E = \int \dot{H}_E \, dt = \frac{V_K^2}{2g} + H$$

If we apply the thrust control law (eq. 6) then we get the thrust required when passing through the low level jet of fig. 8. With this ideal thrust control the aircraft passes the windshear without any deviation of speed and flight path. The required thrust is within the limits of the engines. The commanded thrust rate is fairly low and no problem to be realized. Even in a downburst, thrust and thrust rate lie comfortably within the engine limits [12].

A comparison between the ideal thrust and the pilots thrust settings demonstrate that both responses are similar in principle (fig. 8). The pilots thrust setting is typically digitized. This is quite normal since experienced pilots do not set the throttle continually but in steps. A surprising result is the delay of the pilot thrust response compared to the ideal thrust response by a "dead time" of about 30 seconds depending on the kind of low level jet. This includes a response delay of approximately 2 seconds of the engine. The extreme time delay was nearly the same for all 14 pilots involved in this simulator campaign for the fixed base simulator with conventional instrumentation. Variation of different parameters demonstrated primarily the effect of the height of wind maximum in the low level jet (fig. 8). A wind maximum in H = 340 m resulted in a delay time of 40 sec. A less significant parameter is the magnitude of the wind maximum itself.

Similar results were gained in the Airbus A 340 flight simulator in Berlin. When discussing the results one should keep in mind that the Airbus A 340 simulator had an airspeed trend indicator included. The basic equation for this speed trend bar is

$$(9) \qquad V_{\text{indicated}} = V_{\text{measured}} + \frac{dV_{\text{measured}}}{dt} \cdot T$$

The advance time constant T being equal to 10 seconds.

As the response in a low level jet is rather slow and turbulence is not present the question arose whether the motion cue of the simulator would affect the results. Approaches were realized with and without motion. During these trials the motion system was always switched off at touch down since the landing jerk is a typical indication for motion. A surprising result was that pilots could not correctly identify if the motion system was switched on or not (fig. 9) [13]. The time delay was not influenced by motion. This minor effect of motion gives an indication that the results obtained with the fixed base simulator have the same validity as those obtained with the more sophisticated motion simulator.

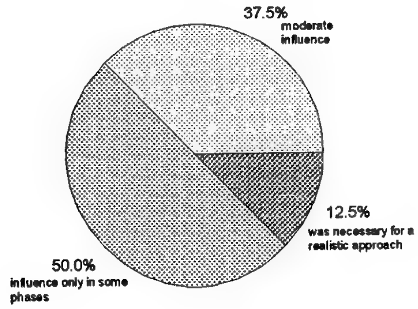


Figure 9: Pilot judgement on the influence of the simulator's motion system (motion off)

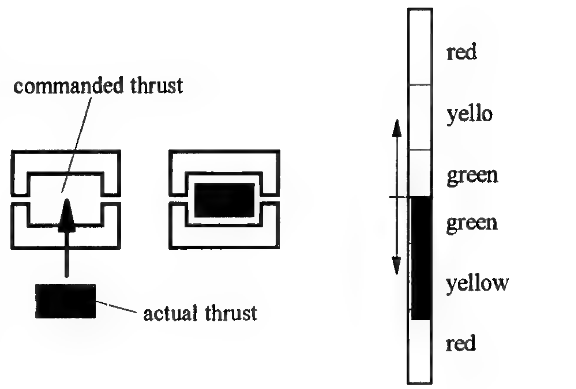
5. Thrust Command Director

The enormous time delay of the involved pilots could be gained in both flight simulators for wide body aircraft as well as for turboprop aircraft. The scatter of the time delays between the different pilots was small. The effect could be quantified but we are still far away to give a proven explanation for the pilot's behaviour. It may be assumed, that the human being has not only limitations in the higher frequency range, but also in the lower frequency domain. The human being has more or less the frequency response of a band pass. The higher frequency domain is well examined as handling qualities. Do we have to expand the handling quality domain to lower frequencies? The difficulty to identify accelerations of longer duration e.g. in a lift is well known as "adaption" in the medical community. Nevertheless, the question can not be answered in this paper.

To keep the pilot in the control loop the flight director is a well proven and successful device. The function of the pilot is more or less that of an actuator. The pilot has to keep the needles of the flight director close to zero. The needles itself are controlled by the flight control system. With such a flight director an aeroplane can be controlled precisely and safely. The pilot can supervise the control system easily.

We have pointed out that the throttle control will follow the thrust command formula (eq. 6) to keep airspeed and flight path constant even in severe windshear simulation. Can we persuade the pilot to response in the same manner?

Pilots have learned to set the throttle only if necessary. High throttle activity is typical for a flying student. What we need is the indication of the actual and the commanded thrust. The actual thrust is represented in the vertical speed indicator. If we add a second pointer to represent the commanded thrust, all necessary information for the pilot is available. A previous simulator investigation [16] with the DLR motion based simulator (out of service since several years) was only partly successful. Only ten of fourteen pilots involved in the simulator programm "survived" the well known downburst that caused a crash in New York on June 24, 1975 (fig.1). The main problem was the typical position of the vertical speed indicator. Measurements of the eye movement indicated that this instrument was scanned only every 7 seconds. This scanning rate was probably not high enough. The investigations were stopped with the result that an indicator located in the center is necessary to present the relevant information for the pilot. A solution for this is the electronic flight instrument system (EFIS) that can be easily reprogrammed. An easily programmable symbol generator has been especially developed at the Insitute of Flight Guidance and Control to represent digital maps on a commercial EFIS display [14]. With such a display thrust and thrust command can be located in the central panel area (fig. 10, 11) [13]. Additionally, the pilot needs an indication of the energy situation to distinguish if throttle response is required or not. A column indicator (fig. 10) for the energy height deviation from the trimmed prosition changes its colour depending on the level of alert (green, yellow or red). An energy height deviation of more than 10 meters is dangerous [10, 15]. With such a situation indicator the pilot provides a non linear control. In the green range no input is needed and the yellow range already indicates that throttle activities are required. The integration of these symbols is shown in fig. 11.



a) b)

Figure 10:
a) Thrust and thrust command indicator
b) Energy height indicator with alert level dependent colouring

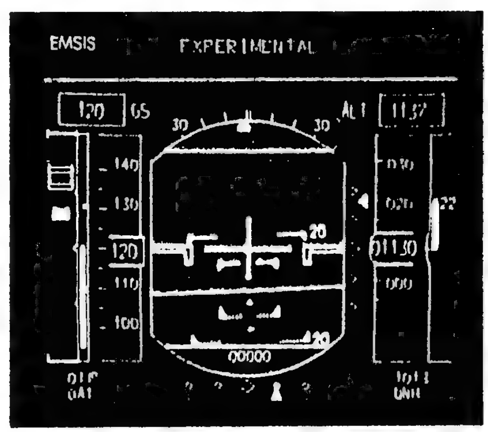


Figure 11: Modified primary flight display (PFD)

With the thrust command director human pilots are able to fly the aircraft with similar results as those obtained by automatic flight control systems. The total delay time is reduced down to engine delay time (fig. 12). Additionally, the results with conventional instrumentation as well as with speed trend indication in the Primary Flight Display (PFD) are demonstrated. The relevant flight and thrust variations are plotted in fig. 13. The relative risk as well as the energy height deviation are plotted in fig. 14 for the different type of indicators. Table 2 demonstrates the percentage of accidents and go around decisions obtained with different indicator concepts.

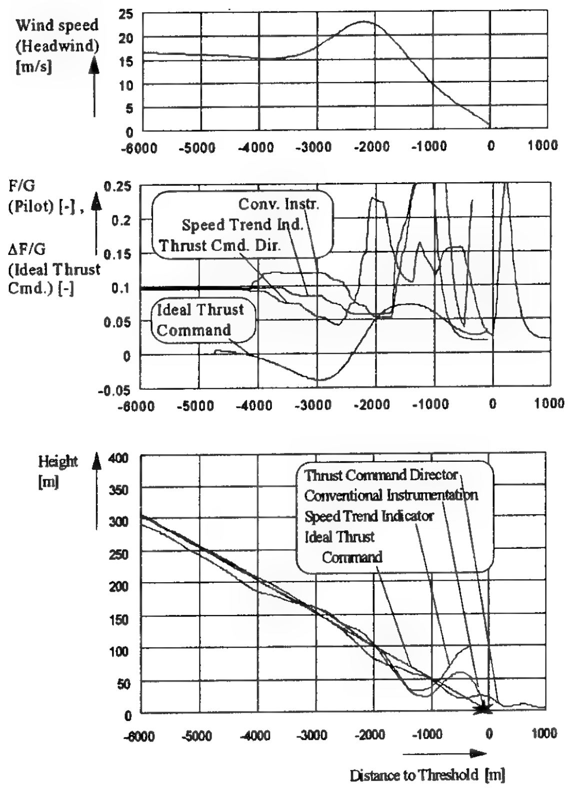


Figure 12: Approaches through 'worst case' low level jets with different indicator concepts

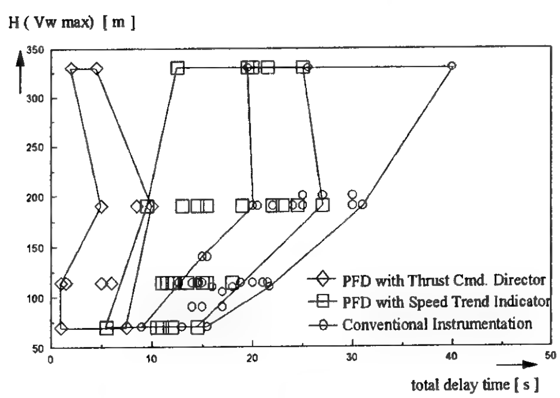


Figure 13: Comparison of the total delay time obtained with different indicator concepts

	conv. instr.	speed trend	EMSIS	automatic
accidents	32 %	3 %	0 %	0 %
go-arounds	28 %	21 %	7 %	0 %

Table 2: Accidents and go-around decisions for the different indicator concepts (EMSIS: Energy Management, Surveillance and Information System)

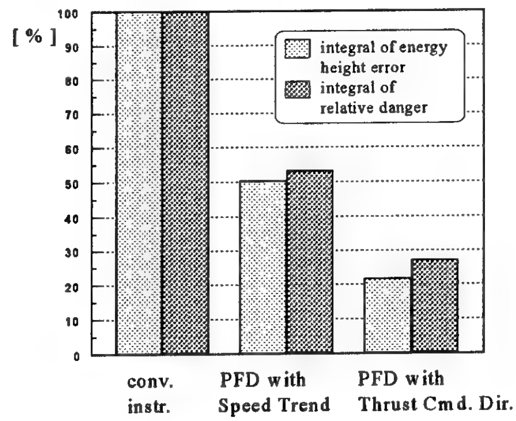


Figure 14: Energy height error and relative risk during the approaches related to conventional instrumentation

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ASRA - A New Tool for In-flight Simulation
Current Status and Actuation Studies

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1. ABSTRACT

The Flight Research Laboratory (FRL) of the Institute for Aerospace Research (IAR) is in the process of developing an Advanced Systems Research Aircraft (ASRA) based on a Bell 412HP helicopter. This paper describes the current status of this facility, and discusses the approach being taken towards fly-by-wire actuation in this high control power host vehicle. The primary problem faced in designing a research fly-by-wire (FBW) actuation system for this aircraft is that of maintaining an adequate level of flight safety throughout the entire flight envelope, while limiting its simulation capabilities as little as possible, this is discussed. A scheme for compound actuation of the 'critical' axes is introduced. Initial off-line simulations of various failure modes are described and the results presented. The purpose of this paper is to present to the community a proposed approach to this problem and to describe some initial studies in support of the design concept used.

2. BACKGROUND

The FRL had operated variable stability helicopters in the airborne simulation and systems development modes for nearly three decades. The current working aircraft, the Airborne Simulator, based on a Bell 205 A-1 is, in fact the third generation of such machines developed at the laboratory. The FRL approach to fly-by-wire for research has always been a generalized one, with the aircraft not married to a specific control system architecture. The Airborne Simulator comprises the host aircraft, a set of dual mode, full authority, high bandwidth actuators, a general purpose computing system a set of state and pilot input sensors and a variety of pilot displays. There is no embedded software and no dedicated fly-by-wire control system as such. This has left the laboratory free to adopt control system structures appropriate to the experiment in hand: state feedback, control feed forward or model following techniques are all used as the demands of specific projects dictate.

Some years ago, particularly when developing a data base for use in drafting ADS-33C [1], it was realized that the Bell 205, with its two bladed teetering rotor system, had neither the control power nor the agility to investigate those areas of increasing importance to the helicopter community. It was therefore decided to replace the Airborne Simulator with a new research aircraft having a rotor technology more representative of today's production models. After a study of several available helicopters, with either fully articulated or hingeless, bearingless rotor systems, it was decided to purchase a Bell 412HP to be the new host vehicle. The final decision to acquire this model came only after a short, but intensive, flight test study conducted at the Bell facility at Mirabel in Canada [2]. With the cooperation of Bell Helicopters/TEXTRON, the company demonstration aircraft was instrumented by the FRL . The instrumentation package was the FRL Micropack [3] , a high quality instrumentation and data recording system developed at the laboratory and used extensively for parameter identification studies, augmented by specific pilot control input sensors. In this configuration the aircraft was flown through a complete set of ADS-33C Part 4 manoeuvres and subjected to specific parameter identification control sequences (modified 3,2,1,1 inputs and manually flown frequency sweeps).

This exercise confirmed the suitability of the Bell 412 for its intended research role and the aircraft was acquired in April 1993.

3 . THE DEVELOPMENT PROCESS

3.1 Overview

In common with many similar organizations internationally, the National Research Council has been subject of severe budget restraint for the past several years and there is no indication that this will change in the foreseeable future. Therefore, the approach to development of ASRA is perforce one of slow stages towards the final goal of having a fully fly-by-wire general purpose flight mechanics research vehicle. At the same time, it was felt desirable to have the machine produce useful research work before that final goal was met. This has led to a staged development process, in which the aircraft is to be instrumented and provided with in interim data processing and recording system with the ability to present the pilots with project specific instrument displays before the application of fly-by-wire actuation and the final flight control computing system. It was also determined that, to exploit its potential agility to the fullest, it would be necessary to install a real-time loads measuring system on the aircraft and that this installation *had* to precede any further parameter identification studies.

3.2 Current Status

At this time, sufficient instrumentation has been added to the aircraft to permit useful research, particularly in the area of civil helicopter IFR flight. The present fit comprises:

- a project power distribution system
- an engineering workstation
- a Litton LTN 92 Inertial Reference System with Integrated GPS
- a Trimble GPS receiver with a UHF data link for real time differential GPS positioning

Paper presented at the AGARD FVP Symposium on "Flight Simulation — Where are the Challenges?", held in Braunschweig, Germany, from 22-25 May 1995, and published in CP-577.

- static pressure, dynamic pressure and total temperature sensors
- pilot control input sensors
- provisions to drive the standard electromechanical instruments from the workstation.
- a DAT based data recording system, controlled by the workstation

As a research system, the aircraft installations are supplemented by a compact, self contained GPS ground station which produces the real time corrections sent to the aircraft via the UHF data link and a VAX workstation for data transcription and analysis.

3.3 Planned Installations - Near Term

Two significant installations are planned for the near term.

Speech Recognition System. As part of the private sector support for ASRA, the Canadian Marconi Company (CMC) has donated a CMA 2082 CDU for installation in ASRA. The specific unit designated for this will contain a speech recognition capability, which represents the product of research conducted at this laboratory by a cooperative group comprising CMC, the NRC and the Neil Squire Foundation with the support of DND (CRAD). In addition, a complete suite of bus controllable avionics has been ordered to replace the standard items presently in the aircraft. This will enable the conduct of specific and realistic research into the use of Direct Voice Input (DVI) in the cockpit.

Stereoscopic Flat Panel Display. In cooperation with Litton Systems Inc, the laboratory is shortly to install a unique stereoscopic head-down display for generic display research. The unit is an active Liquid Crystal Display, capable of mono or stereo graphics without encumbering the pilot with any additional equipment. The unit is currently running in a ground based display development facility and has been used to develop a range of three dimensional "highway in the sky" symbology sets for steep decelerating IMC approaches to a helipad. In the aircraft these will be used to assess pilot performance while using and acceptance of displays of this nature relative to more conventional displays and flight directors in the same task.

3.4 Fly-by-Wire System

Converting the ASRA to a fly-by-wire aircraft involves several distinct tasks:

- Selecting, constructing or purchasing suitable pilot control inceptors and mounting these at one of the pilot stations.
- Selecting, mounting and integrating a suitable flight control computing system.
- Determining a suitable scheme for actuation.
- Acquiring suitable electrically signaled actuators
- Designing the physical installation of the selected actuators.
- Performing the physical installation

The constraints placed on these activities by current fiscal restraint in Canadian Government funding have had a major influence on this entire process. Not only are funds limited, but the scheduling of available moneys is also a factor. Because of this some decisions have been heavily influenced by the availability of in-house equipment. Pilot inceptors will, at first, be one or other of the several side-stick controllers already in house. Consideration of a conventional control loading system to simulate conventional controls will be addressed at a later time. The flight control computer will be a 68040 processor based VME system operating under OS -9. This will provide compatibility with the on board engineering workstation and with identical hardware being installed in other laboratory aircraft. Actuators have been selected and ordered, but the actuation scheme has yet to be finalized and is, in fact the subject of current study. The remainder of this paper will be devoted to discussion of the actuation system. Although the actuation scheme has yet to be finalized and is, in fact the subject of current study, actuators have been selected and ordered.. The remainder of this paper will be devoted to discussion of the proposed actuation system.

4.0 FLY-BY-WIRE ACTUATION IN ASRA

4.1 General Considerations

"Hardover" Incidents in the Bell 205. The Bell 205 Airborne Simulator has always been driven by full authority high bandwidth actuators which, in a single channel system have always left the aircraft potentially vulnerable to a full deflection hardover in the FBW mode. The FRL has relied on hardware health monitoring and software safety related modules to assist the safety pilot in preventing catastrophic results from such an occurrence. In practice, very few *full* hardovers have ever been noted and none were permitted by the safety pilot to progress to a point at which the aircraft was at serious risk. Only one hardover has ever been due to failure of an actuator or its associated electronics, one was attributable to a sensor failure and one due to a switching logic error in the early days of the aircraft's operational life, when the flight control computations were predominantly analogue. This implies that the majority of hardover or unplanned step displacements of the controls experienced in the Airborne Simulator were commanded by the flight control computing system. Such commanded occurrences have become extremely rare since flight control computer programming was switched, first to floating point assembler and then to a high level language from assembler with integer arithmetic.

Safety Factors in the Bell 205. Although it would be difficult to prove academically, the FRL is convinced beyond doubt that the ability of the safety pilot to ensure the aircraft's integrity under failure conditions is due to three main factors. Firstly, *all* actuator commands generated by the FBW system are reflected back to the safety pilot's controls. This implies that all actuation must be in parallel with the safety pilot's controls. Secondly, the safety pilot remains always hands on and is provided with an instinctive FBW disable/disengage control in the form of a cyclic paddle switch, mounted so that it can be activated quickly and instinctively by one of the two fingers which are always kept resting upon it. The safety pilot quickly learns what is the norm for any given control system and tends to react very quickly when the perceived pattern changes for no clear reason. Finally, the 205 has a comprehensive health monitoring system that continually examines the states of electrical power supplies and hydraulic pressure *at the actuators* and disengages the FBW system the moment a fault is detected. Based on these observations made over the 22 years of the Airborne Simulator's service life, the FRL has decided that ASRA should share the same essential

characteristics, even if they are achieved by different techniques.

Considerations for ASRA. Despite the excellent record of safety under abnormal conditions experienced in the 205, it is considered that an identical system would provide inadequate safety margins were it to be fitted to the Bell 412. The Bell *Soft In Plane* rotor system of the 412 displays appreciably higher control power and considerably less response delay than is seen in the 205 (Approximately 72 ms for the Bell 412 compared to 180 ms in the Bell 205). It has been felt from the first that a method must be found to limit the aircraft's response to hardover in the actuation hardware itself (in addition to an essentially similar system to that in the 205). Several options were examined, including:

- shaped pilot valve porting to tailor the frequency/amplitude response of a single actuator
- the use of multiple actuators per channel and
- the use of software monitoring of the actuators to inhibit fast, large amplitude responses.

The first option, the more elegant and simpler to install, had to be abandoned because funding limitations would not permit our paying for the non recurrent engineering which would be involved in the design and development of such actuators. The third option implicitly rate limits the actuators. This was felt to be undesirable because of the high probability of distorting the simulation responses of the aircraft. It was decided to adopt dual actuators (or rather, two actuators operating as a single 'compound actuator') for the critical axes (pitch and roll) and to use a certified flightworthy design and to employ single actuators of the same type in the yaw and heave axes.

4.2 The Actuation Scheme.

Again, the FRL experience with the Bell 205 has helped to ease the decision making process for ASRA actuation. The close similarity of the two helicopters enabled us to decide that the collective and yaw channels could be safely serviced by a single actuator each and to limit compound actuation to pitch and roll, these being deemed the critical axes for failure at very low altitude.

Yaw channel hardover failures in the Bell 205 have proved to be startling but never to endanger the aircraft significantly and the tail rotor of the Bell 412 is identical to that of the 205.

A full collective DOWN failure at very low level could cause the aircraft to strike the ground heavily, but probably not in such a way as to put the crew at risk. Such a failure is also, to an extent self limiting. If the aircraft is VERY close to the ground, then there will be insufficient time for it to reach a high vertical velocity, while as the height becomes greater, there is more time for the safety pilot to react to ameliorate the situation.

Pitch and roll disturbances, in contrast to those in yaw and heave, can rapidly become a danger to the aircraft when very close to the ground, especially during manoeuvring flight. This led us to search for a method which would enable us to achieve limited aircraft upset in the event of an actuator malfunction or, the more real case, an inadvertent very large actuator step demand. The success of some models used in recent experiments in the area of limited authority attitude SCAS systems [4], themselves borrowed from old autopilot technology, led us towards a dual actuated approach to motivating the pitch and roll channels. In this approach, one actuator is permitted full authority, but at a limited rate of extension, while a second is permitted high bandwidth, but limited authority. The output from the rate limited unit is differenced with the command signal and this "error" is used to drive the high bandwidth device. This scheme is shown in Figure 1

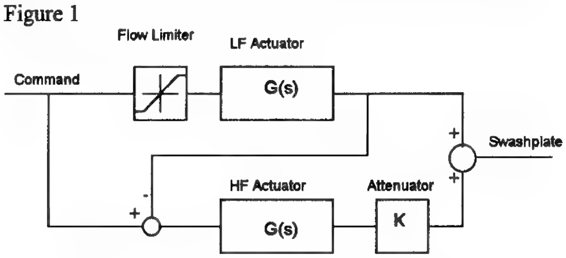


Figure 1 Compound Actuator Schematic

This scheme provides a system in which the high bandwidth actuator moves only when the full authority actuator reaches its rate limit and there will be a linear relationship between command and aircraft control run displacement until such time as the rate limited actuator and the high bandwidth actuator are simultaneously limited. In practice, the rate limit and the contribution to final output of the fast actuator will be set physically by use of a hydraulic flow limiter and a mechanical summing linkage between the actuators.

4.4 Basic Actuator Performance

Given an actuator configuration of this nature, it is necessary to accept that it will impose some limitations on the FBW envelope of the host vehicle due to its inability to respond in a linear manner to all driving signals. The actual device chosen for use in ASRA is the HR Textron Part No 41000360, a three inch throw linear electrically signaled actuator with built in fail-safe (free output rod) mode. This unit is designed to an airworthiness critical specification and has been employed on other fly-by-wire vehicles, both fixed wing and helicopter (notably the Sikorski Shadow). The manufacturer gives a small signal model for this actuator in servo form as shown in Figure 2.

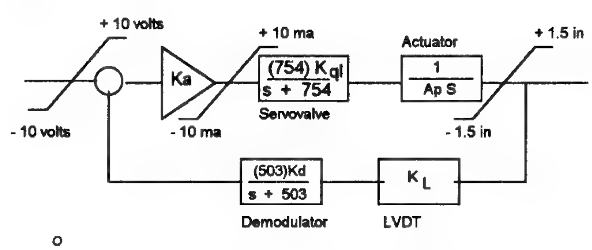


Figure 2 Servo Block Diagram Model

This block diagram was implemented in a non real time simulation and subjected to frequency domain analysis, the results being shown in Figure 3. In this figure, the amplitude ratio plotted has the units of in/volt and the driving signal was a frequency sweep of 0.01 to 40 rad/sec in 120 seconds, with an amplitude of 3.33 volts (33% of maximum).

4.5 Compound Actuator Performance

The structure in Figure 1 was modeled, with the actuator blocks G(s) being replaced with the structure shown in Figure

2. The flow limiter values and the gain K were varied to examine their effects on the frequency response of the compound actuator. A sample of the results is shown in Figure 3 (See section 5.2 for Case definitions). This figure clearly shows that the lower the authority of the high bandwidth actuator, the greater the performance loss in the compound actuator. However, .the figure also shows that it is quite possible to build a compound actuator which approaches closely to the performance available from a single

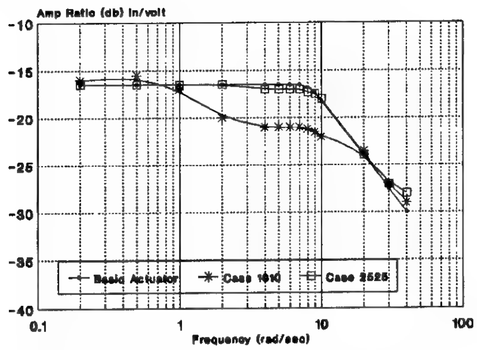


Figure 3 Actuator Matching Performance

unit, while maintaining a significant measure of protection to the crew. It should be noted, too that these simulations were conducted using a relatively large amplitude driving signal, covering a range in which the vast majority of routine, even aggressive pilot inputs fall. However, it is not sufficient to show that the actuation scheme can be built to provide adequate performance for the simulation task without examining the response of the aircraft to hardover failures with the various combinations of rate limit and authority proposed for this system.

5. AIRCRAFT RESPONSES

5.1 Swashplate Geometry and Worst Case Failure.

It is intuitive to accept that a worst case failure scenario for the low level helicopter is that which would produce the largest attitude disturbance in the least time. The geometry of the swashplate/aircraft actuators in the Bell 412 is such that the simultaneous and controlled operation of two actuators is necessary for a clean pitch or roll response from the aircraft. Both cyclic actuators contribute to both the pitch and roll commands to the main rotor that is, if both actuators move in unison, the swashplate rotates in pitch, while if they move in opposition, the swashplate rolls. It follows that if a single actuator runs away due to a fault downstream of the drive signal, the aircraft will suffer a two axis disturbance, but that the swashplate will deflect, in each axis, only about one half of its total capability in that axis. At the same time, if the FBW system is currently active, any disturbance caused by failure of a single actuator, unknown to the active control system, then the error condition will be automatically opposed by the remaining actuator, softening the total effect of the failure. This , together with the observations made in paragraph 4.1 lead us to believe that the 'commanded' hardover, where both actuators receive a maximum drive command from the FBW computer due to programming or sensor error, represents the worst case failure mode. Consequently, investigations of potential aircraft disturbances have been concentrated on this concept.

5.2 Aircraft Modeling

For the purpose of this investigation, a simple second order transfer function model of the primary lateral control response characteristics of the unaugmented Bell 412 at the hover was constructed. This model was built empirically to match data taken by the laboratory on the actual host airframe (Reference 2). To obtain a good match between the phase roll off of the aircraft and model required a time delay of some 72 ms, however, since the form of the phase curve may be related to other high order effects, the time delay was subsequently removed to ensure a 'worst case' low frequency response from the model when subjected to step inputs. The model was subjected to excitation from four separate sources; these were the outputs from actuator models which themselves were subjected to 100% step input demands, the actuator models were

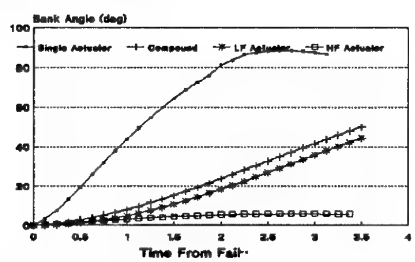
- A basic single actuator as described in Figure 1
- The output of the compound actuator of Figure 2
- The individual outputs from the component values of the compound actuator, that is, the rate limited output of the LF actuator and K times the output of the HF actuator.

A series of test cases was run using this set-up, making the rate limit and gain K experimental variables. For convenience, the configurations used have been assigned case identifiers for future reference: the case identifier is a four figure group, the first two being the rate limit on the LF actuator in percent per second, the second two the extent limit on the HF actuator in percent, eg. case 1520 would define a compound actuator with a rate limit of 15%/sec and a limit on the HF actuator of 20% of total throw.

For each case, results were obtained for three major conditions. Firstly, the aircraft was allowed to respond open loop to the actuator signals; this was to obtain a feel for the kinds of disturbance possible in the first few seconds after a failure or abnormal command. Secondly, two forms of pilot response were simulated, the first based on pilot intervention after a certain recognition time, the second triggered by the aircraft reaching a given attitude change from trim. Both these may be valid trigger mechanisms to induce safety pilot intervention. The first implies the case of a step input being fed back to the safety pilot's cyclic stick; rapid intervention is assured (this remark is based on the author's personal experience of having flown as safety pilot in the Airborne Simulator for over 15 years). The second case is similar to the kind of response engendered in the presence of a more subtle failure, such as the runaway of a rate limited actuator. In both cases the pilot model was a simple low pass filter at 5 rad/sec plus a 300 ms delay which returned the control signal to zero. This was intended to represent a rather abrupt resumption of control and initial recovery by a safety pilot pre conditioned to anticipate a failure. The 300 ms is intended to represent the minimum neuromuscular delay expected of an alert safety pilot and the return to zero a rather conservative response, since experience shows that a safety pilot usually applies a positive control spike against the initial disturbance before entering a closed loop stabilization mode of control.

6. SIMULATION RESULTS

6.1 Open Loop Responses.
Figure 4 shows typical examples of the open loop response of the aircraft to various hardover failures. On this are identified the traces of how the aircraft would respond to each of the fault conditions specified in 5.2 above. The advantage to the safety pilot of compound actuation is clear from this diagram, even a commanded hard-over gives the pilot a significant increase in available reaction time before excessive attitude disturbances occur.



Case Figure 4a 1010 Response, No pilot Intervention

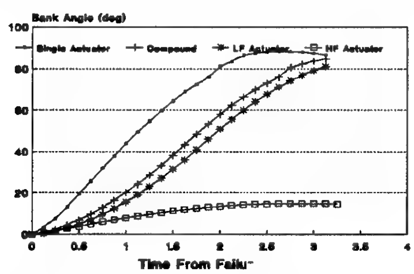


Figure 4b Case 2525 Response, No Pilot Intervention

The disturbances for the 16 cases studied are summarized in Tables 1 to 3. Table 1 shows the maximum attitude reached at first peak when only the HF actuator fails, Table 2 contains three items per LF actuator rate limit, the time to reach 45 degrees of attitude, the peak attitude reached and the time to reach peak attitude. Finally, Table 3 summarized in the same way the results obtained for runaways of the complete compound actuator, using the case identifiers described earlier to characterize the compound actuator characteristics.

Table 1 Maximum Attitude Excursion for Step Failure of HF Actuator Without Pilot Intervention

HF Limit (K)	Max Attitude (deg)	Time to Max Attitude
0.10	8.86	2.83
0.15	17.73	2.86
0.20	26.59	2.88
0.25	35.44	2.90

These data give considerable confidence that the basic compound actuator strategy is a viable one for maintaining an acceptable balance between fly-by-wire performance and crew safety, especially as a simple actuator of the same type indicated 1.15 seconds to 45 degrees of bank with a maximum attitude of 88.45 degrees in 3.05 seconds. Selection of a set of compound actuator characteristics now depends on a judgment of how great a disturbance can be tolerated when operating close to the ground. To assist in making this decision, the two 'pilot intervention' cases were examined.

Table 2 Disturbance Characteristics for Failure of LF Actuator Only Without Pilot Intervention

	Time to 45 (sec)	*Max Attitude (deg)*	*Time Max (sec)*
10	3.54	75.11	6.25
15	2.68	81.11	4.85
20	2.25	84.07	4.26
25	1.98	85.61	3.94

Table 3 Disturbance Characteristics for Failure of Both Sections of the Compound Actuator Without Pilot Intervention

Case ID	*Time to 45 (sec)*	*Max Attitude (deg)*	*Time Max (sec)*
1010	3.03	75.28	5.73
1015	2.35	81.39	4.51
1020	2.01	84.30	4.01
1025	1.79	85.79	3.74
1510	2.54	75.96	5.17
1515	2.05	82.15	4.17
1520	1.79	84.86	3.77
1525	1.61	86.20	3.55
2010	2.12	77.49	4.61
2015	1.79	83.36	3.86
2020	1.60	85.67	3.55
2025	1.46	86.77	3.39
2510	1.80	79.91	4.10
2515	1.58	84.83	3.59
2520	1.44	86.58	3.37
2525	1.33	87.39	3.25

6.2 Pilot Intervention Cases
Pilot Intervention After Time Delay. The pilot recovery action described in 5.2 was modeled with time delays to failure recognition of 0.25,0.5,0.75,1.0,1.25 and 1.5 seconds. Only the full compound actuator hardover was considered, and the results have been characterized as the peak attitude reached after failure and subsequent pilot intervention in Table 4. In this table, cases which resulted in an attitude excursion of over 20 degrees have been highlighted. A set of typical time histories for this model are shown in Figure 5

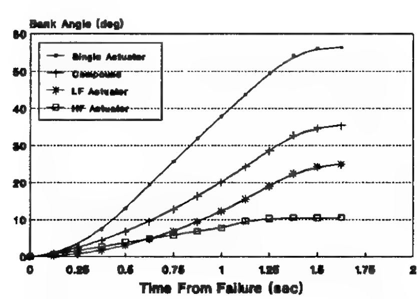


Figure 5 Case 2525 with Pilot Intervention After 0.5 seconds Delay

Pilot Intervention Triggered by Attitude. These cases were examined because experiences with the Bell 205 have shown that subtle, or insidious failures are possible which lead to a slow attitude divergence without sufficient feedback to the safety pilot's cyclic controller to trigger intervention. Such conditions have on occasions even been long and slow enough to permit verbal discussion between the pilots, typically the safety pilot saying "Are you doing this ?" to the evaluation pilot before a failure condition was confirmed. Depending on the rate limit finally chosen for the ASRA LF Actuators,

Table 4 Peak Attitudes Following Compound Actuator Failure and Pilot Intervention After a Recognition Delay

Case ID	*Delay 0.25*	*Delay 0.50*	*Delay 0.75*	*Delay 1.00*	*Delay 1.25*	*Delay 1.50*
1010	5.92	9.02	12.51	16.33	20.41	26.67
1015	7.57	11.20	15.19	21.33	27.09	33.18
1020	9.16	13.34	17.83	26.34	33.77	41.69
1025	10.70	15.43	20.43	31.34	40.45	50.21
1510	7.17	11.27	16.03	19.45	23.91	28.47
1515	8.81	13.46	18.71	24.45	30.57	36.97
1520	10.40	15.59	21.34	29.45	37.25	45.48
1525	11.94	17.68	23.94	34.45	43.93	53.56
2010	8.41	13.53	19.55	22.54	27.38	32.26
2015	10.06	15.71	22.22	27.53	34.04	30.75
2020	11.65	17.85	24.68	32.53	40.71	49.25
2025	12.89	20.11	28.73	37.53	47.38	56.63
2510	9.66	15.79	23.07	25.60	30.82	36.03
2515	11.30	17.97	25.74	30.58	37.48	44.51
2520	13.18	19.94	27.45	35.57	44.14	53.00
2525	14.43	22.19	30.97	40.47	50.63	59.45

failure cases similar to these may be anticipated. Again, the same conditions were applied to the simulated pilot response, that is, after the response trigger, a neuromuscular delay of 300 ms was followed by a very simple low pass return of the control to neutral. Since this type of failure is much more likely to be related to a hardware (particularly analogue electronics) failure than a software or computer hardware failure, a runaway of the LF actuator was considered to be the most representative case and possibly the worst case, since only a subtle ramp signal would be felt at the safety pilot's cyclic, not the step plus ramp which would be the case if the full compound actuator failed. The results for 10, 15 and 20 degree attitude triggers are shown in Table 5

Table 5 - Peak Attitudes Attained and Elapsed Time when Pilot Response was Triggered by Attitude Divergence

Rate Limit	*Trigger 10 Deg*		*Trigger 15 deg*		*Trigger 20 deg*	
	Attitude	*Time*	*Attitude*	*Time*	*Attitude*	*Time*
10%	16.12	2.04	21.58	2.34	26.75	2.62
15%	18.31	1.82	24.18	2.04	29.70	2.25
20%	20.24	1.69	26.45	1.88	32.23	2.04
25%	21.97	1.60	28.48	1.77	34.54	1.91

7. DISCUSSION OF RESULTS

7.1 Permissible Attitude Excursions. The results presented in the previous section offer a rough guide to what might be expected in the way of attitude excursions with a nominal safety pilot reaction to abnormal control activity or uncommanded aircraft motion. What remains is to select a maximum attitude excursion which may be considered acceptable and from there determine the physical characteristics to build into the compound actuators. In considering acceptable excursions, thought must be given to the types of manoeuvres expected of the aircraft in the FBW mode and when close to the surface and the role of the safety pilot in preventing accidents due to system malfunctions. In particular, it is necessary to consider the normal manoeuvring attitudes achieved and what would be the final attitude of the aircraft if the most adverse failure were to occur when at that attitude. For example, if the aircraft was at 45 degrees of bank in a lateral acceleration at, say 10 feet AGL, would a potential excursion of 20 degrees (final attitude therefore 65 degrees of bank) be acceptable ?

7.2 The Role of the Safety Pilot

. Note: The following remarks are based on the personal experiences of the author, who has flown as safety pilot in the 205 for the past 15 years and his observations of three other pilots who have shared this duty in the same period

Table 4 indicates that,. for *commanded* hardover failures, the attitude excursions is critically dependent on the safety pilot's delay in recognizing the failure condition. Experience at the FRL, unfortunately supportable only anecdotally, is that when in a potentially high risk situation, the safety pilot is so "spring loaded" for failures that recognition time is very short indeed. The few failures documented in the past show a total reaction time under these circumstances in the order of 350 to 500 milliseconds, this including both recognition and reaction. There have been several occasions recorded wherein the safety pilot beat the hardware safety system in disconnecting the fly-by-wire system. There are also occasions when the safety pilot causes inadvertent or nuisance disconnects because of his readiness to react very quickly - these are most prevalent when new control systems are in use and he is, therefore, unfamiliar with the normal spectrum of control activity they produce or when he has an unknown 'high gain' pilot in the evaluation position. It is therefore with confidence that we can claim that a human safety pilot, experienced and well trained, has proved a successful final link in the safety of flight during fly-by-wire operations of the Airborne Simulator. If, therefore, the reaction of ASRA to commanded hardovers can be made no more severe than that of the 205, then we can confidently continue this mode of operation without limiting the FBW flight envelope of ASRA.

8.0 FUTURE DEVELOPMENT

8.1 Hardware

It is planned to mount a set of actuators on a ground development rig and examine the efficacy with which the modeled structure can be implemented in practice. The actuators will also be measured for large and small signal performance and for match to the manufacturers model.

8.2 Off-Line Simulations

Off line simulations will be continued to investigate various forms of actuator monitoring to provide protection against post digital hardware failures (amplifiers, demodulators etc). Specific attention will be given to using a software model of the actuators as comparators and, in conjunction with the ground test rig mentioned above, to determine possible error level triggers for automatic disconnect. Such a scheme will have to account for varying actuator loads and system noise.

8.3 In-Flight Manned Simulations

It is proposed to conduct manned simulations using the NRC Airborne Simulator to confirm safety pilot reaction times to the kinds of failures detailed in this paper before committing to a specific set of compound actuator characteristics. The results of these simulations will also be used to determine what kind of monitoring/comparing system might be required.

9. CONCLUSION

On the present time table, it is expected that ASRA will be available for fly-by-wire experimentation in the fall of 1996. Once the conversion has been completed, the vehicle will provide a platform for advanced systems and flight mechanics research which will be significantly more powerful than the current Airborne Simulator

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RESEARCH APPLICATIONS AND CAPABILITIES OF THE NASA/ARMY ROTORCRAFT AIRCREW SYSTEMS CONCEPTS AIRBORNE LABORATORY (RASCAL)

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ABSTRACT

The Rotorcraft Aircrew Systems Concepts Airborne Laboratory (RASCAL) is a UH-60 Black Hawk helicopter that is being modified by NASA and the US Army for flight systems research. The principal systems that are being installed in the aircraft are a Helmet-Mounted Display (HMD) and associated imaging systems, and a programmable full-authority Research Flight Control System (RFCS). In addition, comprehensive instrumentation of both the rigid body of the helicopter and the rotor system is provided. This paper describes the design features of this modern rotorcraft in-flight simulation facility and their current state of development. A brief description of initial research applications is included.

INTRODUCTION

The application of modern digital technology is accelerating with the development of sub-systems, such as flight and fire control systems integrated with helmet mounted displays, that tax the capability of the pilot to accomplish new complex mission tasks. Fortunately, new technologies, such as digital flight control systems, are also available to offset these new demands on the pilot.

Much of the work needed to develop practical pilot-vehicle systems that do not exceed the capability of the pilot can be done in ground-based simulation. However, as pilot workload and the operating environment approach limits, such as in nap-of-the-Earth (NOE) operations, conclusions drawn from the comparatively benign ground simulation environment can result in additional development costs when the technology is transferred to flight vehicles. Consequently, an in-flight simulator in which to evaluate and validate system integration designs is becoming an increasingly important requirement.

Presented at the AGARD Flight Vehicle Integration Panel Symposium on "Flight Simulation - Where are the Challenges?," May 22-25, 1995, Braunschweig, Germany.

In-flight simulators have been an integral part of the development of aircraft technology since the first one was developed in 1947 at NASA's Ames Research Center. In the past, these R & D facilities have typically been limited to the investigation of handling qualities requirements as manifested primarily in the flight control system. Now, the strong impetus to integrate complex avionics and mission equipment in both military and certain civil helicopters is placing critical new demands on the pilot. The influence of these demands on safety and mission effectiveness that can only be fully understood in the real flight environment. The RASCAL is the latest in-flight simulator to be developed at Ames, and it is the most versatile. The combination of its advanced fly-by-wire flight control system and displays capability make it uniquely suited for the simulation of today's complex piloting tasks.

It was determined (Ref. 1) that the Army/Sikorsky UH-60A Black Hawk helicopter was the most appropriate baseline vehicle for RASCAL development. In October of 1989, a JUH-60A, originally used as the Army's Advanced Digital-Optical Control System (ADOCS) demonstrator aircraft (Ref. 2), was loaned to NASA-Ames Research Center by the U.S. Army to develope the RASCAL research facility.

PROJECT OBJECTIVE AND RESEARCH APPLICATIONS

The objective of the RASCAL facility development project is to design and develop an

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airborne laboratory capable of supporting the flight research requirements of several different programs. These programs involve the close cooperation of NASA with the Army, FAA, and the rotorcraft industry.

The joint NASA/Army programs have a common objective: to develop integrated control, sensor, and display technology to increase the capability and safety for all-weather, low-level rotorcraft operations. The individual elements of these programs are:

- Development of flight-validated modeling methods employing system identification and a rotor state measurement system to ensure the development of realizable control laws
- Development and validation of multi-input/multi-output control synthesis techniques suitable for rotorcraft which allow physical insight into the design problem
- Integration of vision sensors; including television, infrared, and millimeter wave radar with an on-board terrain data base and appropriate guidance algorithms to allow manual and pilot-directed, automated low-level flight
- Development of the pilot-vehicle interface, including an advanced helmet-mounted display and integrated, active controllers to enhance the pilot's situational awareness and increase the operational maneuver envelope of the vehicle

NASA programs that are in support of FAA and the civil rotorcraft industry include the Civil Rotorcraft IFR Terminal-Area Technology Enhancement Research (CRITTER) program that is conducting research to

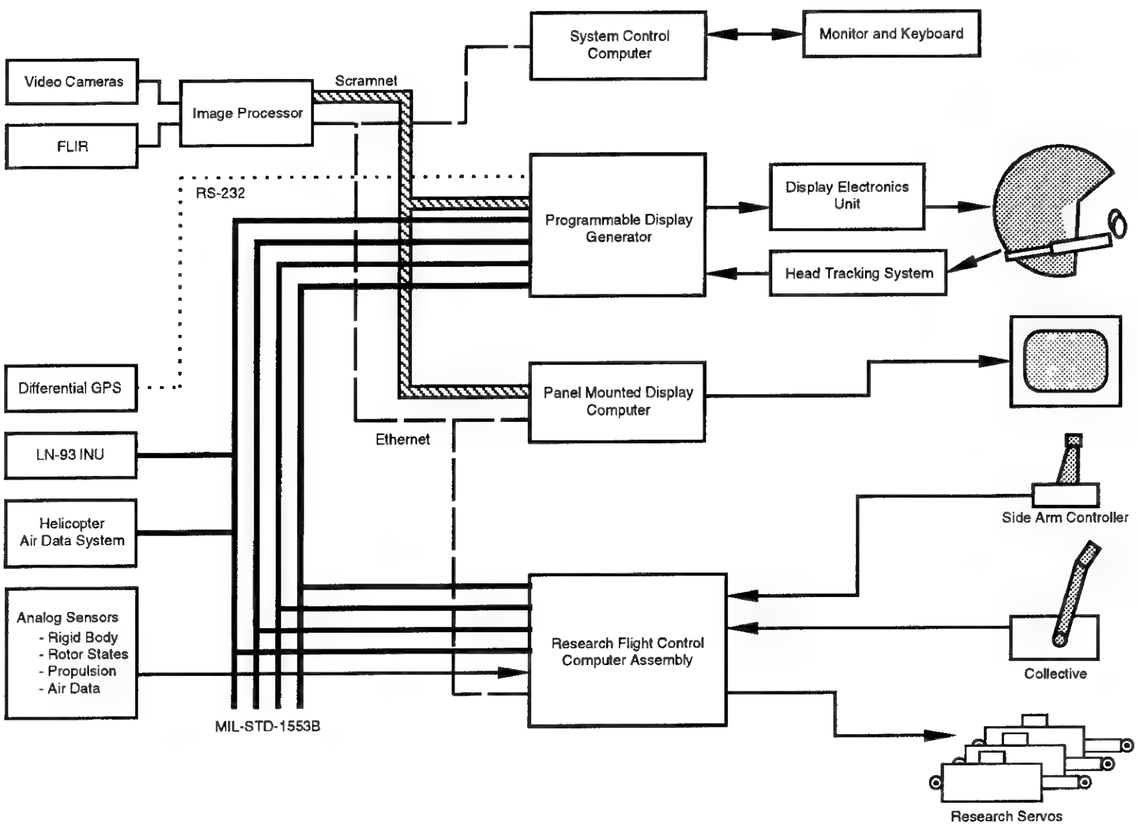

Figure 1. *RASCAL Research System Architecture*

improve the operating safety and community acceptance of rotorcraft, including Tilt Rotors. Preliminary research describing the development of one-engine-inoperative flight techniques to improve safety and payload is described in Refs. 3 and 4. In addition to this NASA-initiated research, the RASCAL helicopter can be used by the helicopter manufacturing industry as a common national facility to conduct flight tests.

RESEARCH SYSTEM DESCRIPTION

The RASCAL is being developed in an incremental fashion which allows the conduct of research programs during the development period. As additional capability is installed, it remains part of the research system for future use in research programs. Flight test programs which have been conducted on the RASCAL include:

- Acquisition of video data which, when coupled with the recorded aircraft rigid-body state data, allow the development of obstacle ranging information for presentation to the pilot (Ref. 5.)
- Development of a laser-based measurement system to determine the flapping, lead-lag, and pitch angles of each of the rotor blades. Initial data have been acquired and are being evaluated. These data will allow the development of refined models of rotor dynamics for simulation use.
- Development of a helicopter approach guidance methodology using differential GPS to minimize noise for helicopter operations in urban environments. (Ref. 6)

The RASCAL helicopter is configured as an in-flight simulator with the evaluation pilot in the right cockpit where the controls are mechanically disconnected from the aircraft and electrically connected through a full-authority fly-by-wire flight control system developed specifically for the R&D role. The left cockpit controls remain mechanically connected to the JUH-60A to serve as a safety pilot station for monitoring the system and for assumption of control in the event of a system fault. The RASCAL research system architecture, shown in Figure 1, provides a flexible and highly capable research facility while ensuring flight safety. This system will include:

- A high quality data acquisition system, including rigid body, rotor state, and propulsion system sensors, suitable for the acquisition of experimental data and for implementation in flight control applications.
- A programmable, fly-by-wire research flight control system including high-performance servos, a flight control computer with a hardware/software architecture necessary for the computational throughput requirements of the various research control concepts, and a high-speed data bus with sufficient capacity for the anticipated bus traffic.
- An in-flight researcher interface for monitoring the experiments and for effecting configuration changes to allow productive use of flight time.
- An on-board precision navigation system suitable for low-altitude flight, including a ring-laser gyro Inertial Navigation Unit (INU) and a Differential Global Positioning System (DGPS).
- Appropriate passive (e.g., TV or FLIR) and active (e.g., radar or laser) sensors for image-based guidance and navigation including obstacle detection/avoidance.
- An extensive on-board computational capability for real-time image processing, vehicle motion estimation, guidance algorithm generation, and pilot's display generation.
- Terrain data base storage for low-altitude navigation.
- A programmable cockpit display system consisting of two panel-mounted color displays suitable for the presentation of guidance information and digital maps.
- A color, wide field-of-view, Helmet-Mounted Display (HMD) combining flight status and command information with sensor-based imagery and computer based imagery.

Two key elements of the RASCAL research system which support operation of the JUH-60A as an in-flight simulator are the Helmet-Mounted Display System and the Research Flight Control System. The remainder of this paper describes the requirements and the designs of those two systems.

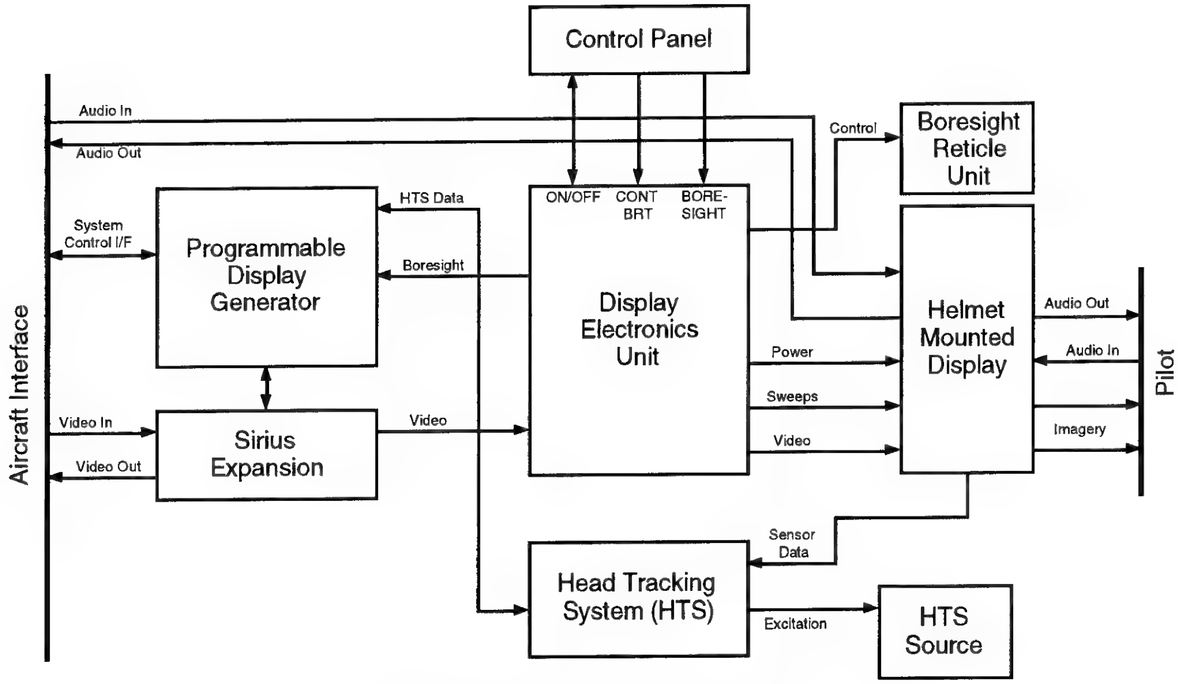

Figure 2. *Helmet -Mounted Display System*

Helmet-Mounted Display System

The RASCAL Helmet-Mounted Display system is being developed for NASA by Kaiser Electronics and consists of the helmet with its color display generating capability, a head tracking system to allow presentation of airframe or inertially stabilized information to the pilot, a display control panel allowing the pilot to control the system, a programmable display generator to process aircraft state and guidance information and produce the symbology for presentation to the pilot and a boresight reticle unit for registration of the display symbology and imagery to the aircraft axes. A functional block diagram of the system is illustrated in Figure 2, and the principal system features are listed in Table 1. Additional elements include the video sensors which provide a forward-looking image to the HMD system.

Helmet-Mounted Display (HMD): The HMD consists of three parts: the Aircraft Retained Unit (ARU), the Pilot Retained Unit (PRU), and the Display Electronics Unit (DEU). The ARU includes two cathode ray tubes (CRTs), mechanical color filters, relay optics necessary to project the CRT image to the pilot, and a head tracker sensor. The color display is generated by two high-brightness monochrome CRTs, one for each eye, in front of which are placed rotating color filters, divided into two or three color sections. The data on the CRTs are synchronized with the rotating color filters, so that the appropriate datum appears when the corresponding color section of the wheel is in front of the CRT viewing surface. This mechanically shuttered field-sequential color generation technique provides the RASCAL HMD with two-color or full three-color capability depending on the filter set that is installed. To permit operation in locations of high ambient lighting, the color filters can be removed resulting in a monochromatic presentation. The performance provided by this technology is listed in Table 1. The relay optics are a 10 element color-corrected system which provide a 40 degree monocular field-of-view. The optics use a combiner element which provides 30% see-through to the outside world. The ARU is connected to the DEU via a cable assembly which includes a quick disconnect allowing rapid emergency egress.

Table 1. RASCAL Helmet-Mounted Display Principal Features

PARAMETERS	PERFORMANCE
Field-of-View	40 Degrees Circular (monocular) Overlap 50% Total FOV - 40 deg (Ver) X 60 Deg (Hor)
Modes of Operation, Brightness & Chromaticity	1 Color Yellow 1136 fL u' = 0.146 v' = .565 2 Color Green 297 fL u' = 0.1066 v' = .5819 Red 83.55 fL u' = 0.4701 v' = .529 3 Color Green 297 fL u' = 0.1066 v' = .5819 Red 41.7 fL u' = 0.4701 v' = .529 Blue 8.81 fL u' = 0.0696 v' = .3177
Exit Pupil	15mm on axis; 10mm Off-axis
Eye Relief	17mm, Eye Glass Compatible
Contrast Ratio, Viewing Condition	1 Color Yellow CR 4.34 10,000 fL Ambient, Class II visor 2 Color Green CR 3.91 3,000 fL Ambient, Class II visor Red CR 1.81 3,000 fL Ambient, Class II visor 3 Color Green CR 52.4 30 fL Ambient, Class I visor Red CR 8.23 30 fL Ambient, Class I visor Blue CR 2.52 30 fL Ambient, Class I visor
Line of Sight Positional Accuracy	Horizontal - 5.5 mrad Vertical - 3.5 mrad
Shades of Gray, Viewing Condition	1 Color Yellow 4.48 SOG 10,000 fL Ambient, Class II visor 2 Color Green 4.18 SOG 3,000 fL Ambient, Class II visor Red 1.97 SOG 3,000 fL Ambient, Class II visor 3 Color Green 11.67 SOG 30 fL Ambient, Class I visor Red 6.32 SOG 30 fL Ambient, Class I visor Blue 2.92 SOG 30 fL Ambient, Class I visor
Luminance Variation	±20% within 10 degree diameter ±30% within total FOV
Combiner Transmissivity	30%
Display Controls	Brightness (left/right) Contrast (left/right) Boresight On/Off
Input Power	115 VAC 3 Phase 400 Hz
Registration (in overlap)	Horizontal ± 5mrad Vertical ± 1mrad
Ocular Alignment	+1/2 diopter, -1/8 diopter

The PRU consists of the helmet shell, liners, microphone, and earphones. The helmet is custom fit to an individual pilot's head. No alignment is necessary other than preflight boresighting. The liner, when inserted into the PRU and fitted, provides a close fit with air circulation for comfort. With the exception of the comfort fit liner, no part of the head-borne HMD system components make facial or eye contact. The ARU and PRU are firmly held together by a bayonet-type mechanical latch. The DEU provides the electronic interface between the Programmable Display Generator (PDG), the ARU, and the Display Control Panel (DCP). It provides video signal conditioning, CRT drive signal generation, color filter control, and power for the ARU. The total head-borne weight of the HMD is less than 5.5 pounds, and the center-of-gravity is +0.7 in. ±0.1 in. forward and +0.6±0.1 in. above the center-of-gravity of the head. The helmet-mounted display and ARU are shown in Figure 3 and Figure 4, respectively.

Display Control Panel (DCP): The DCP provides the pilot with the capability to control power to the HMD system, adjust brightness and contrast of each display and to conduct the initialization boresight operation.

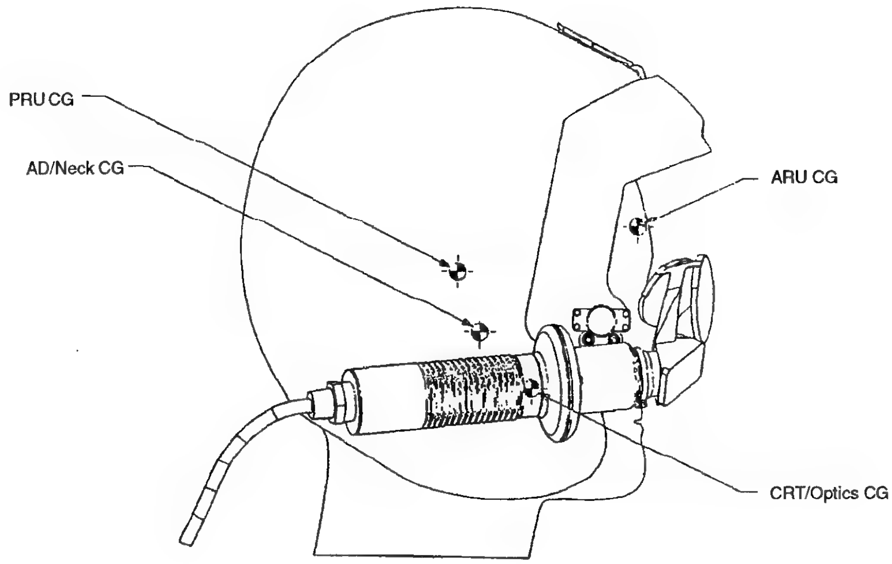

Figure 3. *Helmet-Mounted Display*

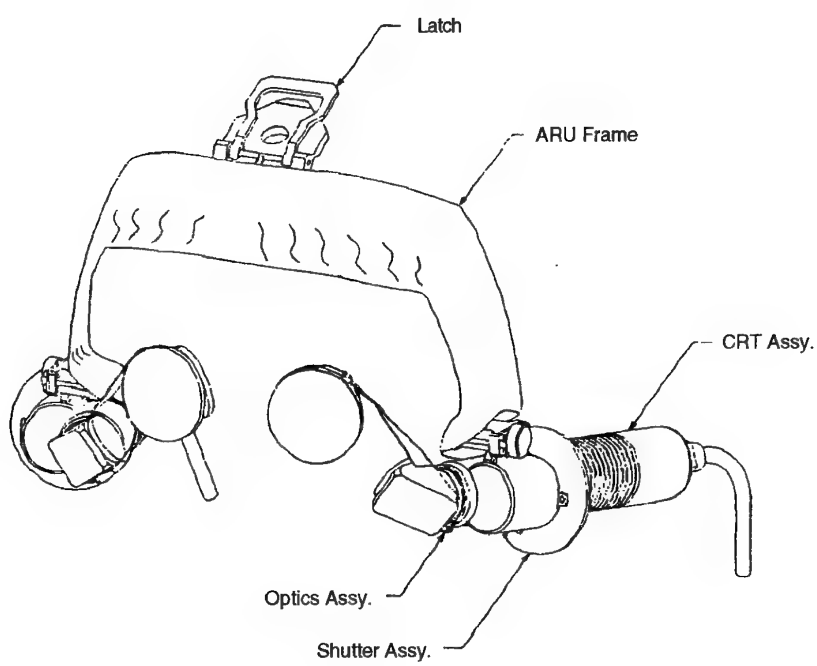

Figure 4. *Aircraft Retained Unit* (ARU)

Head Tracking System (HTS): The HTS is a ruggedized version of the Polhemus FASTRACK™ tracker. It consist of an aircraft-mounted source, a helmet-mounted sensor, and a rack-mounted electronics chassis. The HTS provides the following performance:

- Angular coverage: ±180 degrees azimuth, ±90 degrees elevation & roll
- Translational coverage: 16 inches on each axis
- Angular resolution: 0.44 mrad
- Translational resolution: 0.1 inch
- Static line-of-sight accuracy: 2.6 mrad RMS
- Update rate: 60 Hz
- Transport delay: ≤16.67 msec
- Noise: no perceptible dither to the displayed image

Programmable Display Generator (PDG): The PDG is a Silicon Graphics Onyx Reality Engine 2 deskside work station which has been ruggedized for the flight environment It is packaged with a VME compatible chassis which provides system expansion capability. The PDG and associated software and firmware constitute a programmable graphic/alphanumeric/symbology generator with high-resolution color and monochrome display generation capability to provide the required field-sequential imagery to the HMD. The PDG is programmable in the C programming language and provides access to low-level graphics primitives from the high level language. The hardware and software are capable of generating complex, real-time, dynamic displays and computer generated imagery, utilizing double-buffered hardware that produces flicker-free images. The PDG is also capable of communicating with the in-flight researcher interface system. The PDG accepts inputs from the head tracking system and provides input/output (I/O) via Ethernet, MIL-STD-1553B and RS-232 data busses.

HMD Symbology Software: The initial flight display software to be used during HMD acceptance testing and early flight evaluations was derived from a display format developed by NASA and implemented on the Army's STAR UH-60 (Ref. 7). The symbology associated with the display is shown in Figure 5. It features inertially referenced flightpath symbology as well as screen-fixed symbology which can be viewed against the background real world or overlaid on video imagery from the forward-pointing cameras. Initial research to be conducted with this format will extend the effort reported in Ref. 7 (which used a first-generation narrow field-of-view monochromatic monocle display) to take advantage of the RASCAL's wide field-of-view color capability.

Nose Mounted Camera System: The camera apparatus consists of two monochrome interlaced video

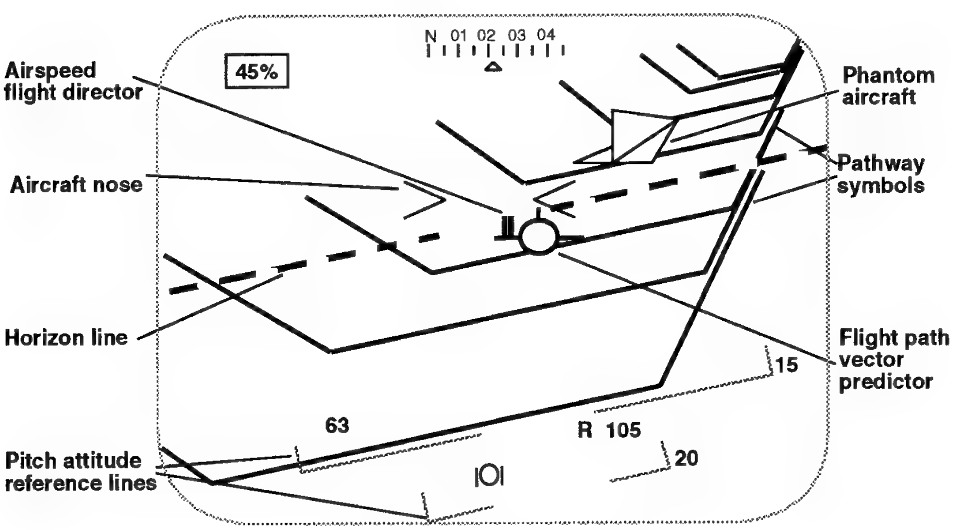

Figure 5. *HMD Symbology*

cameras mounted 1 meter apart on a horizontal bar attached to the nose of the RASCAL helicopter. The cameras have a focal length of 6 mm, a field of view of 58X45 degrees, and they are electronically shuttered with a 1/1000 sec exposure time to reduce image smear due to camera motion. The video imagery from the cameras is time-tagged using video time inserter units and recorded using two video recorders onboard the RASCAL. The images are acquired at the rate of 30 frames/sec per camera.

Research Flight Control System

The requirements and design philosophy for the development of the RASCAL Research Flight Control System (RFCS) are described in Ref. 8. Key aspects of the RFCS architecture and components are presented below. Currently, the Helicopter Division of the Boeing Defense and Space Group together with a team which includes Lear Astronics and Moog are under contract to design and build the RFCS. Boeing and its sub-contractors, Lear Astronics and Moog, have presented a detail design of the RFCS at a recent Critical Design Review. Information provided at that review is the source for many of the details presented in the following sections.

RFCS Architecture. The RFCS architecture, shown in Figure 6, implements a full-authority fly-by-wire capability while retaining the unmodified JUH-60A mechanical flight controls as backup. This architecture is fail-safe; that is, critical RFCS faults cause immediate disengagement of the RFCS and reversion to the JUH-60A mechanical flight controls.

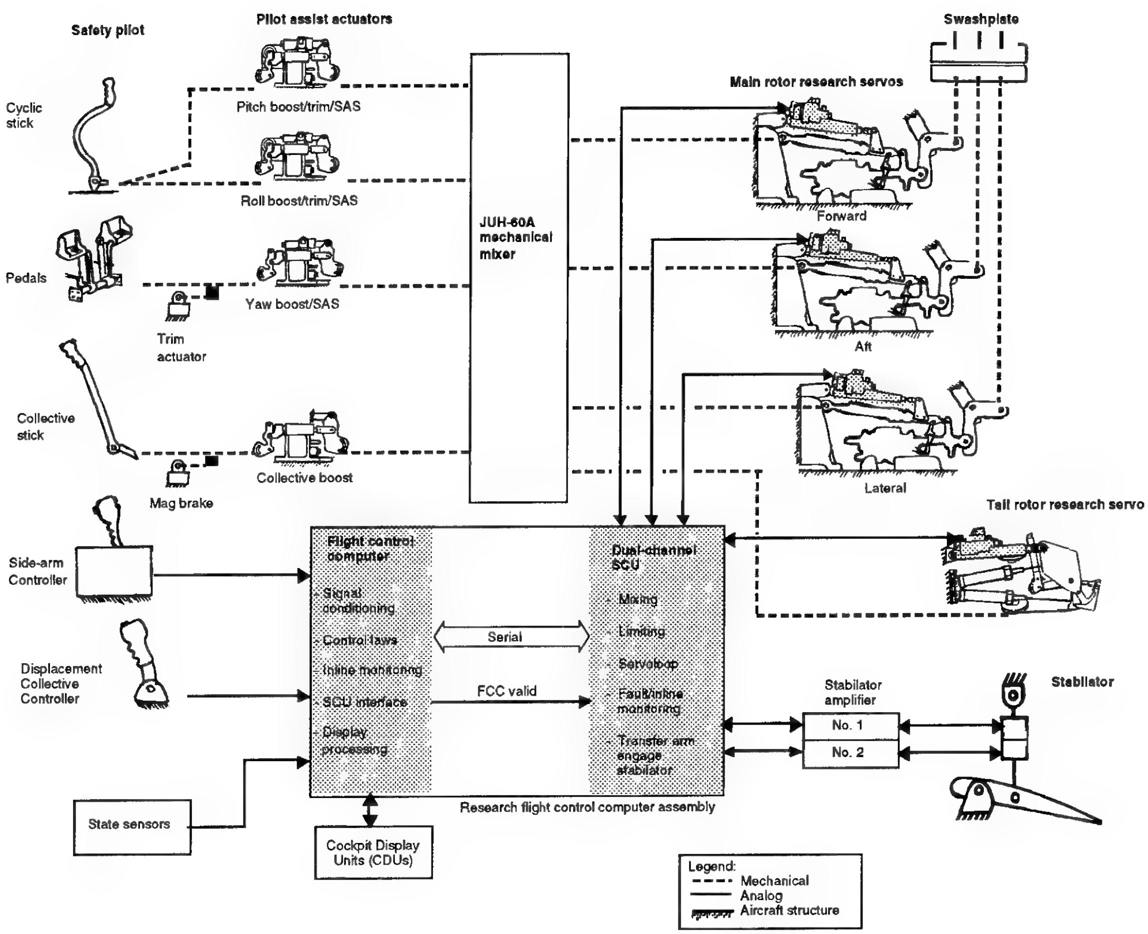

Figure 6. *RFCS Architecture*

The main components of the RFCS are:

- Research Flight Control Computer Assembly (RFCCA)
- 3 Main Rotor and 1 Tail Rotor Research Servos
- Transfer System
- Pilot Controllers
- Aircraft State Sensors
- Pilot and System Operator Cockpit Display Units (CDUs)

The RFCCA is a high performance computer assembly which will process sensor input, compute the experimental control laws, and monitor RFCS performance. It controls the three main rotor research servos and the tail rotor research servo. The main rotor research servos are mounted on the upper crown area of the JUH-60A and provide inputs to the primary boost servos while backdriving the safety pilot's cyclic and collective controls. The tail rotor research servo is mounted in the vicinity of the tail rotor gear box and provides inputs to the tail rotor servo while backdriving the safety pilot's pedals and collective control. The transfer system provides the means for transferring control form the JUH-60A mechanical flight controls to the RFCS and vice-versa. It is designed with sufficient redundancy to ensure that either of the pilots or the safety monitors resident in the RFCCA can reliably disconnect the RFCS. The RFCCA has a multitude of I/O resources to support many pilot controller and aircraft state sensor types. Initially, the RASCAL will be equipped with a 3-axis side-arm controller and a displacement collective control. In addition, two Cockpit Display Units (CDUs) will provide the capability for the pilot or the system operator to set control modes, adjust control parameters, and get RFCS health information.

RFCS Components. Salient features of the major RFCS components are described below.

RFCCA: The RFCCA architecture, shown in Figure 7, includes the two functional components, the Flight Control Computer (FCC) and the Servo Control Unit (SCU), whose requirements were described in Ref. 8. This architecture provides in one line-replaceable unit an FCC with high-performance I/O and

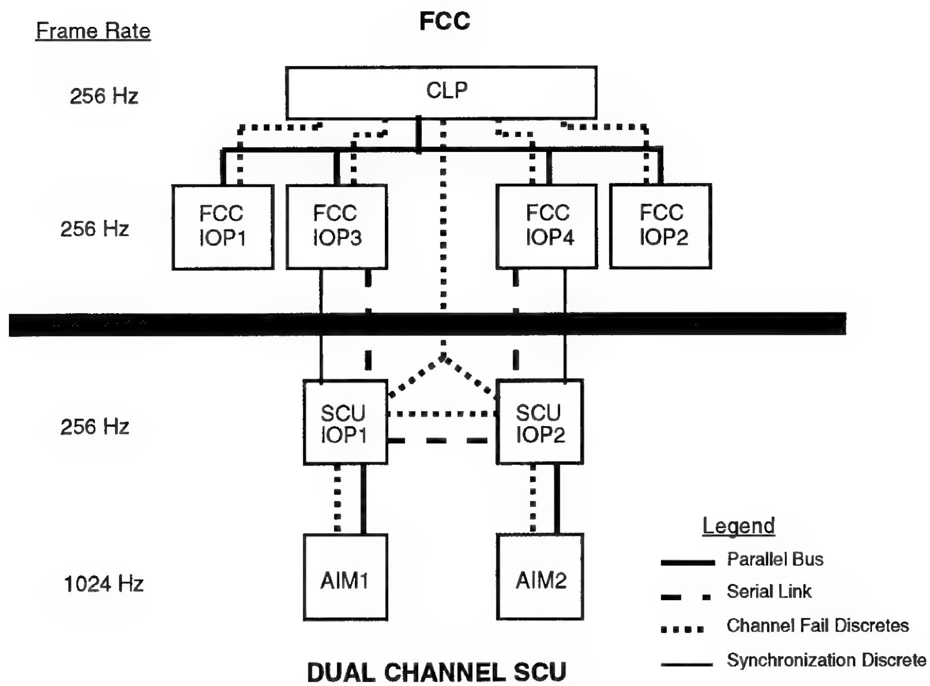

Figure 7. *RFCCA Architecture*

computation throughput for aircraft state acquisition and control law computation and an SCU for fail-safe RFCS control and monitoring. Inside the RFCCA, the FCC and the SCU are physically segregated from each other. They communicate through dedicated high-speed serial links, synchronization discretes, and channel fail discretes.

Table 2. *IOP Attributes*

Microprocessor:	TI 320C30, 32-bit Digital Signal Processor
Clock Speed:	21 MHz
Throughput:	10.5 MIPS
Program Memory	64K×32 (EEPROM)
Data Memory	8K×32 (SRAM) 2K×32 (Dual Port RAM)

Table 3. *CLP Attributes*

Microprocessor:	IDT R3081W with on-chip floating point unit
Clock Speed:	33 MHz
Throughput:	24 MIPS / 4 MFLOPS
Program Memory:	1M×32 (FLASH) 1M×32 (SRAM)

Table 4. *FCC I/O Resources*

DC Analog Inputs	160 (40 per IOP)
DC Analog Outputs	16 (4 per IOP)
AC Analog Inputs	36 (9 per IOP)
Discrete Inputs	52 (12 each for IOPs 1,2, and 4; 16 for IOP 3)
Discrete Outputs	20
MIL-STD-1553B Serial Data Buses	4 dual-redundant buses (1 per IOP)
RS422 Serial Data Buses	2 (CLP) 4 (1 per IOP)
Ethernet	1 (CLP)

The FCC is comprised of 4 digital signal processor-based Input/Output Processors (IOPs) and a RISC-based Control Law Processor (CLP). IOP and CLP attributes are summarized in Table 2 and Table 3. The IOPs and the CLP execute at a 256 Hz frame rate and are required to synchronize with each other every frame. The IOPs provide the FCC with a substantial capacity to perform sensor I/O and filtering. A summary of FCC I/O resources, most of which are provided by the IOPs, is shown in Table 4. Operating at a 60% duty cycle, each IOP can sample, scale, and float 60 analog inputs, process eight 20-word MIL-STD 1553B messages, and filter (with 4th order filters) 85 variables every 3.9ms frame. I/O data is passed between an IOP and the CLP through the IOP's 2K×32 bytes of dual-port RAM. The CLP accesses the dual-port RAM through a 32-bit system bus.

The software structure in the IOPs and the CLP allows the configuration of the FCC I/O to be managed through configuration tables in the CLP software. These tables are downloaded to the dual-port RAM on power-up to provide each IOP with information defining analog input scaling and filtering, analog output scaling, discrete input debouncing and logic, and MIL-STD 1553B message definitions. Thus, only the CLP software needs to be changed in order to accommodate changes in the sensor types and attributes.

The SCU is a dual-channel design with each channel consisting an IOP module (identical to those used in the FCC) and an Actuator Interface Module (AIM). It is responsible for controlling the four research servos, the evaluation pilot's collective actuator and clutch, and the JUH-60A stabilator in response to commands from the FCC. It also provides inputs to and monitors the operation of the transfer system. Most important, though, is the function it performs as the RFCS safety monitor. An extensive set of monitors in the SCU are designed to detect failures in the RFCS components and anomalies in the experimental control laws that would result in unacceptable servo motions or degrade the fail-safe features of the RFCS. In the case of such faults, the SCU will disengage the RFCS without unacceptable transients. A functional schematic of some these monitors is shown in Figure 8. Many of the other RFCS component monitors are omitted from this figure for clarity. Servo commands are monitored for excessive step size and for commands that exceed the control limits. In addition, the servo rates are monitored to ensure that rates above 1/3 of the maximum servo rate are not allowed to persist. This monitor uses a time threshold that is inversely related to the servo rate. The difficulty in developing the appropriate monitors and in selecting the threshold levels in order to detect sensor and control law failures without experiencing excessive nuisance disconnects was described in Ref. 8. In order to provide some flexibility in this area, the SCU will contain four sets of

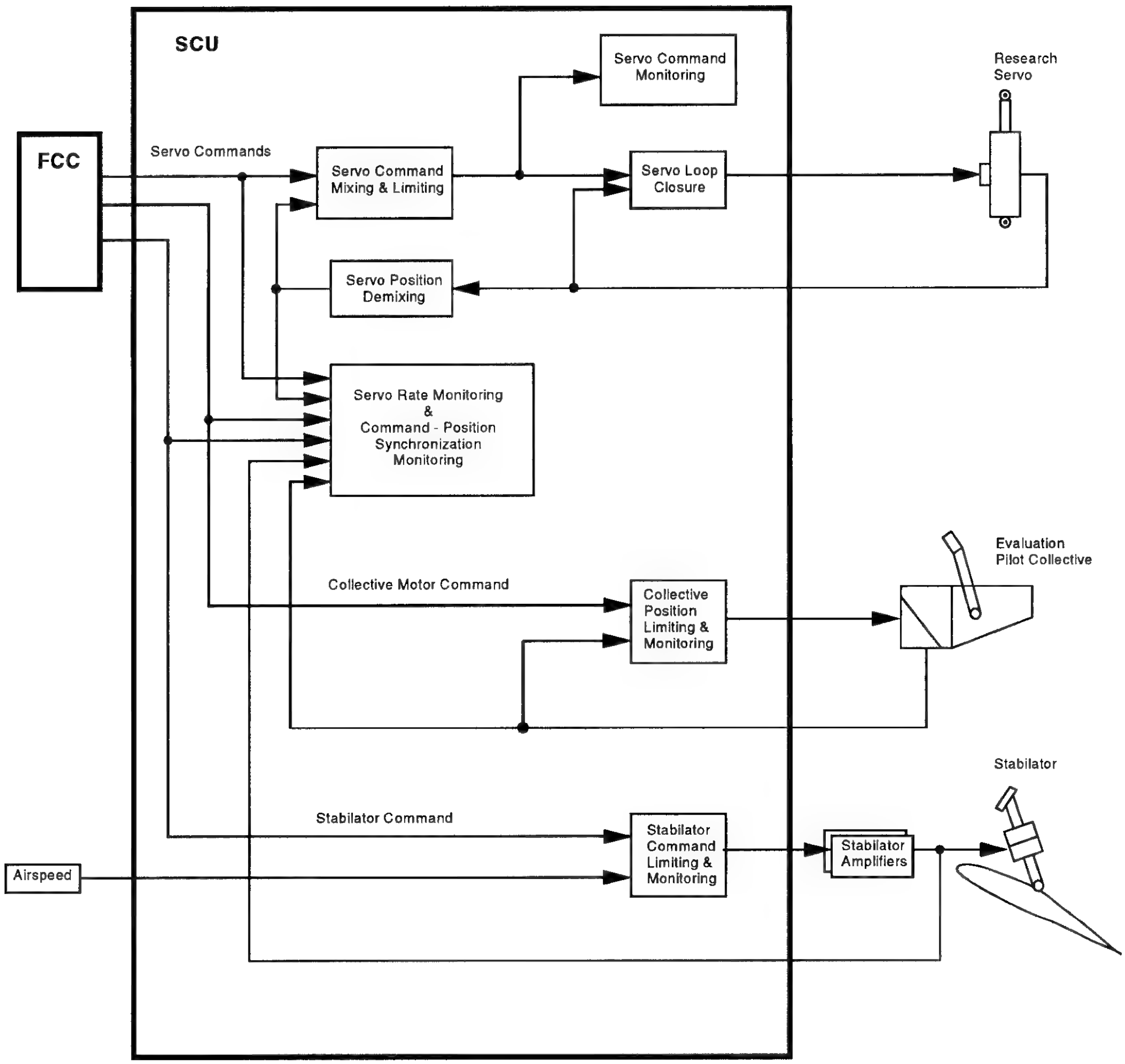

Figure 8. *SCU Monitoring Schematic*

threshold levels from which the pilot can select prior to engaging the RFCS.

Research Servos: The three main rotor research servos and the tail rotor research servo provide high-bandwidth, high-rate, and full-authority inputs to the JUH-60A primary servos. The four servos are identical except for the tail rotor research servo which has a longer stroke and faster maximum rate. A functional schematic of the servos is shown in Figure 9. The servo assembly uses a semi-balanced piston-cylinder design. Each assembly contains a conventional flapper-type, four-way electro-hydraulic servovalve (EHV) with a dual-coil torque motor. Each coil in the torque motor is driven by an SCU channel. The second stage EHV slots are unequal in area to provide a symmetric velocity response for the servos. EHV spool position feedback is used for loop damping as well as for servo fault detection. In addition, each servo includes

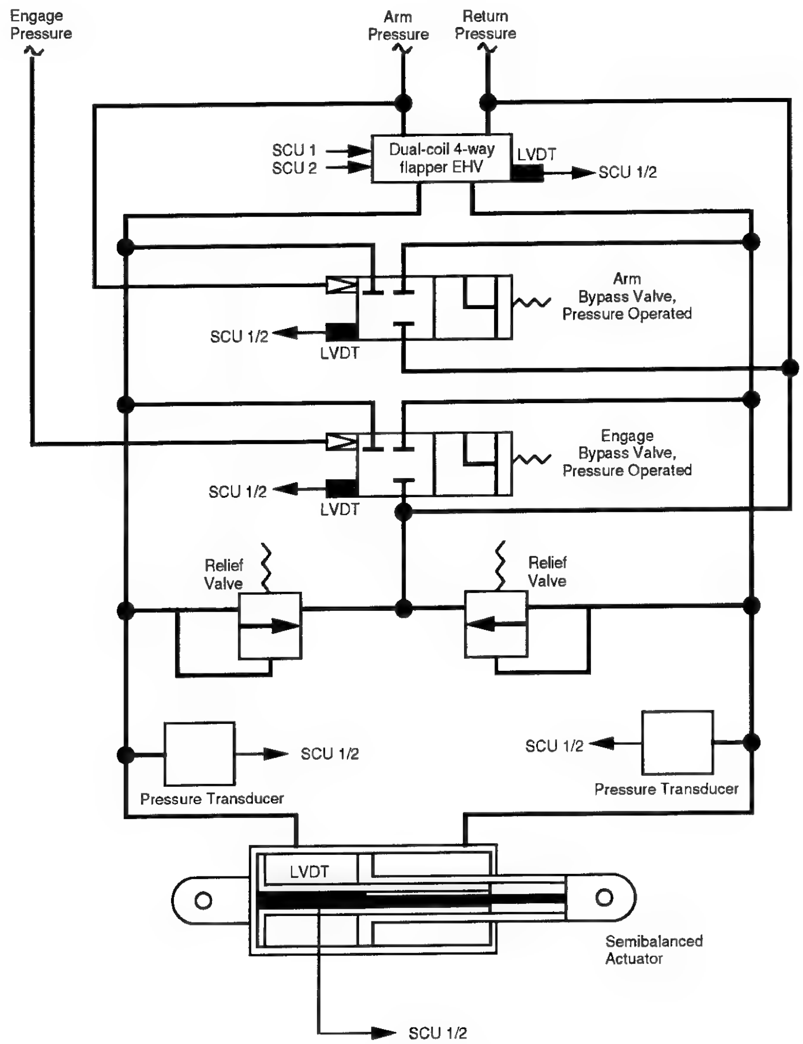

Figure 9. *Research Servo Functional Schematic*

pressure sensors to measure differential pressure across the piston for resonant mode stabilization and load limiting. Pressure relief valves provide a redundant means of load limiting. Each servoactuator package contains arm and engage bypass valves which provide a dual-redundant means to put the servo into bypass mode in the event of RFCS disconnect. These bypass valves are pressure operated and feed back spool position to the SCU for monitoring of the research servo state. The main rotor research servos have a maximum rate of 5 inches per second (equivalent to the JUH-60A primary servo maximum rate) and have a small-signal bandwidth of 8 Hz (defined by phase < 30 degrees). The tail rotor research servo has a maximum rate of 7 inches per second and has a bandwidth similar to that of the main rotor servos.

Transfer System: The transfer system is the set of cockpit switches, relays, and hydraulic shutoff valves that control transfer between the RFCS and the mechanical JUH-60A flight control system. A schematic of the transfer system is shown in Figure 10. The state of the RFCS is determined by the state of a set of dual-redundant relays. These relays directly control the hydraulic shutoff valves that control hydraulic

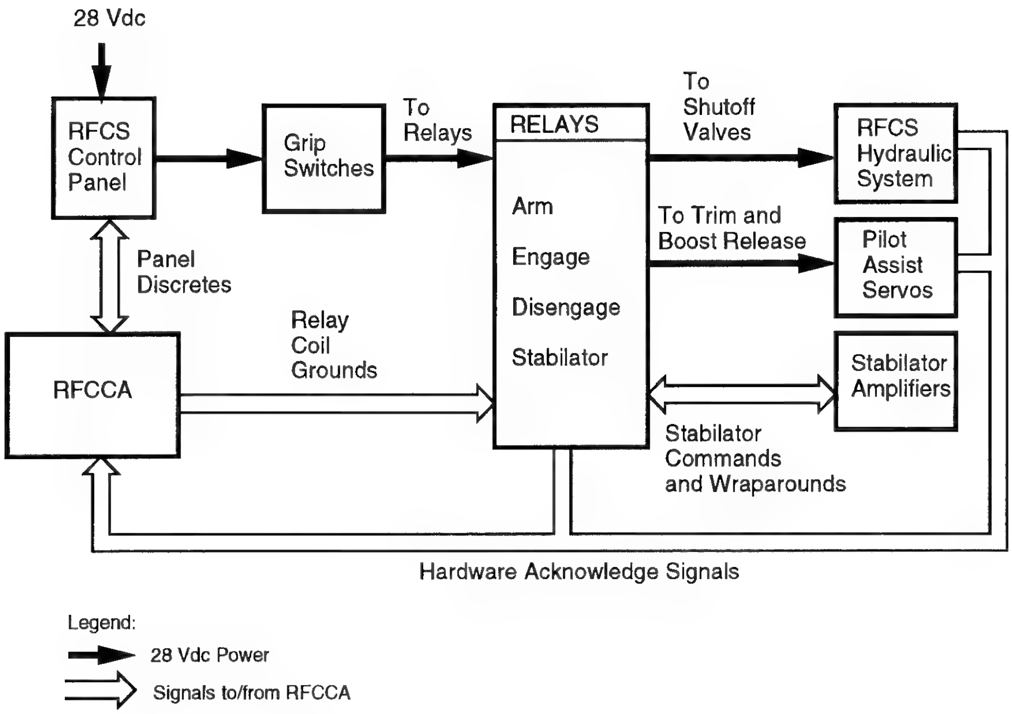

Figure 10. *Transfer System Schematic*

pressure to the arm and engage bypass valves of the research servos. In addition, these relays are used to turn off the JUH-60A trim and pilot-assist servos when the RFCS is engaged. Another set of relays controls the switching of the stabilator commands between RFCS control and the JUH-60A stabilator system AUTO mode control. Through the RFCS control panel and controller grip switches, the evaluation and safety pilots control the 28Vdc going to the arm and engage relays. Each channel of the SCU controls the ground path for one of the dual-redundant relays. With this design, each pilot and each SCU channel has an independent means to disengage the RFCS.

Pilot Controllers: The RASCAL helicopter has the capability to evaluate various pilot controller configurations. Initially the RASCAL will be configured with a small-displacement 3-axis force-gradient right-hand controller for longitudinal, lateral, and directional inputs to the FCC. This controller is identical to that developed for the RAH-66 Comanche helicopter. It also has a limited vertical motion, intended for aircraft trim commands. The grip used with this controller is also that from the Comanche. It includes 8 switches of various types that will be read by the FCC. A medium-displacement left-hand collective controller provides the capability for conventional collective inputs to the FCC. The collective controller includes a low-rate elctromechanical actuator to allow the FCC to backdrive the controller when the RFCS is disengaged. This will ensure that the evaluation pilot's collective is aligned with the safety pilot's collective prior to RFCS engagement, necessary to prevent engage transients. This controller lever/actuator mechanism is based on that used on ADOCS while its grip is from the Comanche program.

Sensors: The wealth of FCC I/O resources provides the RASCAL facility the capability to accommodate a large number of sensors of various types. The initial sensor suite that is directly interfaced with the RFCS includes the following:

- LN-93 Inertial Measurement Unit
- Blade Flap, Lead-lag, and Pitch Laser Position Sensors
- Blade Flap and Lead-lag Accelerometers
- Rotor Azimuth Encoder

- Flight Control Position Sensors
- Nose Boom and Body Mounted Airspeed and Pressure Altitude Sensors
- Helicopter Air Data System with fully gimbaled pitot/static probe
- Radar Altimeter

In addition, other sensor information (e.g. DGPS) is available from the PDG computer via the MIL-STD-1553B data buses.

Cockpit Display Units: Two CDUs will be installed on the RASCAL for control, setup, and monitoring of the RFCS. The CDUs will be used for selecting control modes, adjusting control law parameters, displaying fault messages, executing pre-flight and maintenance checks, and performing INU alignment. A pilot CDU will be mounted in the cockpit center console. A second CDU will be installed at the system operator station in the aft cabin to allow the system operator to participate in test setup and system monitoring. The CDUs will interface with the RFCCA over one of the MIL-STD-1553B data buses.

Control Laws: A baseline set of control laws will be delivered with the RFCS. This set of control laws will be based on those developed for the ADOCS program, but will only implement the core functions of those control laws that are needed to provide good handling qualities. The core functions will include command shaping, automatic trim, rate and attitude stabilization, heading hold, and turn coordination. These control laws will facilitate the rapid integration and checkout of the RFCS before proceeding with the implementation and testing of experimental control laws.

CONCLUDING REMARKS

The unique and highly capable pilot display capability that the RASCAL will provide, combined with its advanced flight control capability, create a research tool which will far surpass the traditional in-flight simulators of the past. The combination of these capabilities creates, in the RASCAL, a full-environment simulator which extends the simulation technology to which we have become accustomed in the ground-based facilities into the unlimited motion-base environment of the in-flight simulator. The RASCAL is precisely positioned to meet the most demanding research and development needs for the rotorcraft industry in the next decade.

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ATTAS & ATTHeS In-Flight Simulators

Recent Application Experiences and Future Programs

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1 SUMMARY

This paper gives an overview of DLR's latest flight experiments, both with the fixed-wing in-flight simulator ATTAS and the helicopter in-flight simulator ATTHeS. After a detailed description of both testbeds and the corresponding ground based simulators, flight test results are presented. These include experiments on in-flight simulation, rate saturation, reconfiguration, flight control laws, handling qualities, and vision based hovering. The paper concludes with a discussion on certain aspects of simulation fidelity.

2 INTRODUCTION

Flying qualities play an essential part related to pilot/vehicle performance (task effectiveness) and flight safety. Due to the large amount of parameters influencing the flying qualities (control system, information/display system, vehicle behavior, environment, flight task, etc.) pilot-in-the-loop simulation is a fundamental element in flight control law design. In-flight simulation (IFS) is recommended as one of the most important tools to be used complementary to ground based simulation. IFS can provide substantial benefits in evaluating control effectiveness of highly augmented flight control systems, new controller types, and pilot information systems. It gives the designers more flexibility to alter the response characteristics of the overall system and to tailor the desired flying qualities.

The great advantages of an in-flight simulator are the realistic visual and motion cues which are the key feedback parameters for the pilot to adapt his control strategy to the vehicle and the flight task. The results obtained from ground simulation studies have to be verified in the "real world", which means, that they have to be tested in flight. To avoid the appearance of problems later in the development phase, which causes expensive delays and increasing costs, requires the utilization of a flying testbed. The demands on high fidelity, high flexibility, and high quality of pilot cues formulate the need to use flying simulators [1].

The great advantage of an in-flight simulator, compared to a ground simulator, is to fly the system in the real world with adequate visual and motion cues for the pilot, and, compared to a technology demonstrator, the capability to vary the system response characteristics. Hardware components like new type of inceptors or information displays can be installed. Besides the complementary incorporation of an in-flight simulator in the development approach of a new flight vehicle and the integrated technologies of pilot vehicle interfaces, additional areas of use are more general and basic research topics [2]:

- Control law design
- Investigation of the response system required by a flight task
- Establishment of credible data for the definition of generic evaluation criteria
- Investigation of interference effects between required overall system response, display format, and inceptor type
- Requirements for system mode blending characteristics
- Investigations of allowable response degradations which occur after system failures

All investigations can be performed without endangering men and/or vehicle. In addition, the development and operation of in-flight simulators inherently include the necessity to solve many problems of a highly augmented system. Consequently, many of the lessons learned and the technical solutions can be transferred directly to the design of operational vehicles.

3 ATTAS AND ATTHES SYSTEM OVERVIEW

For more than 20 years DLR has been successfully operating in-flight simulators for flying qualities research. From 1972 to 1984 a HFB 320 Hansa Jet was extensively used as an in-flight simulator by DLR, the German industry, and foreign institutions. Handling quality assessment technology and data evaluation procedures have been developed and applied. In the early 80's the modern flying simulator and demonstrator aircraft ATTAS (Advanced Technologies Testing Aircraft System) was developed by DLR and Daimler-Benz Aerospace Airbus (formerly MBB) supported by the German Ministry of Research and Technology. Furthermore the Institute of Flight Mechanics of the DLR has developed a research helicopter based on a BO 105. DLR has been operating the ATTHeS (Advanced Technologies Testing Helicopter System) as a testbed and in-flight simulator for more than a decade.

3.1 ATTAS In-Flight Simulator

The complex structure of the ATTAS testbed is outlined in several papers. A brief summary is given in [3]. ATTAS is based on a VFW 614, a twin-turbofan, short-haul, 44-passengers aircraft (Fig. 1).

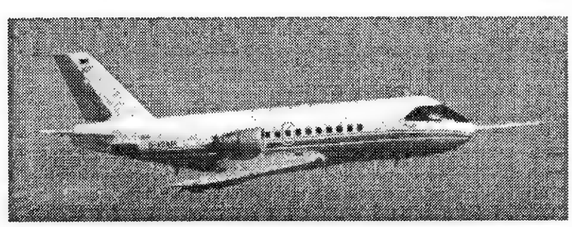

Fig. 1 DLR In-Flight Simulator VFW 614 ATTAS

The VFW 614 is ideally suited as a general purpose testbed due to its size, cabin space, loading capacity, and flight performance. With full fuel, about 3.5 tons of test equipment can be loaded.

Paper presented at the AGARD FVP Symposium on "Flight Simulation — Where are the Challenges?", held in Braunschweig, Germany, from 22-25 May 1995, and published in CP-577.

The flight performance, with cruising altitude of 30 000 ft, maximum cruising speed of 288 kts calibrated airspeed (CAS) and a rather low landing speed of about 100 kts, is adequate for a large transport a/c flight regime representation. Fig. 2 illustrates the ATTAS flight envelope.

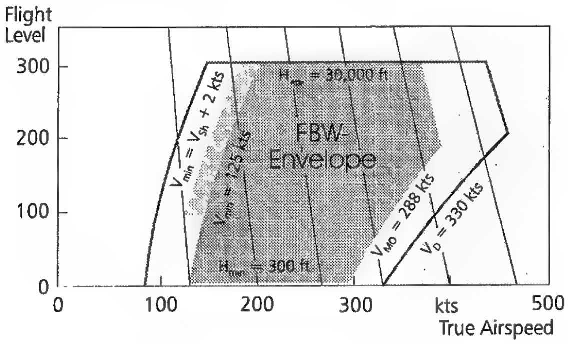

Fig. 2 ATTAS-Flight Envelope

The heart of ATTAS is the fly-by-wire/light system. It is based on a five computer system. [4] and [5] describe the system performance requirements as follows:

- Maximum computational cycle time of 20 ms for all functions
- Redundancy for flight in critical conditions
- Airborne equipment and interfacing of aircraft systems (ARINC 429, MIL-Bus 1553B, etc.)
- Availability of computer capacities for user applications in a high level programming language

To meet these requirements the system has been designed as a two channel computer network consisting of four processors in each channel with one common central processor for communications and data recording. All onboard computers are of MIL-specified LORAL/ROLM types (MSE 14 and HAWK/32). 1.4 MFLOPS are available for experimental functions in the HAWK/32 32-bit computer with up to 8 Mb of memory. The network in each channel is based on a ring structured serial fibre optical bus system.

To give ATTAS a 5-DOF simulation capability five independent control surfaces must be available. Therefore, ATTAS was equipped with a specifically developed "Direct Lift Control" System (DLC) for pitch/heave motion decoupling and gust/load control. For low frequency DLC operation the basic VFW 614 landing flap system can be deflected electrically between 1 and 14 degrees. The rear parts of the landing flaps have been divided into six (three on each wing) fast moving flaps having about 85 deg/sec flap rate and ±35 degrees flap deflection capability for high frequency direct lift modulation.

The main modifications, test equipment, and features of the ATTAS aircraft are summarized as follows:

- Right hand seat safety pilot with conventional control system
- Left hand seat evaluation pilot with fly-by-wire controls
- Freely programmable flight instruments/displays, CRTs
- Digital onboard computer system with fibre optical data bus providing freely programmable control laws and flying qualities
- Duplex inertial reference and digital air data systems
- Comprehensive onboard data acquisition system, recording, and PCM-telemetry
- 15 electro-hydraulic self-monitored actuators, partly duplex, linked to the FBW system by MIL-BUS 1553B
- Dual redundant electric and hydraulic systems
- Fly-by-wire motivators for
  - Elevator
  - Stabilizer
  - Rudder
  - Both ailerons
  - Both engines
  - Landing flaps
  - Six direct lift flaps
- Onboard operator consoles with programmable quick look displays
- Nose boom with angle of attack, angle of sideslip, and true airspeed probe (flight log)

An automatic elevator trim system operates the stabilizer in such a way that the aircraft is always in trim condition. In case the safety pilot reconverts to the basic control system the resulting column and aircraft transients will be negligible.

The ATTAS installed Rate Command - Attitude Hold system was designed especially for the Fly-By-Wire Mode to stabilize the aircraft before switching to the Simulation Mode to run the experiment (e.g. in-flight simulation). There must be a feature to fly the ATTAS in the easiest way. For this the pilot controls the a/c with all control elements in the direct mode. But in case he puts the side stick into the zero position, the last achieved attitude in pitch or roll is kept independently in the pitch and roll axis. For level flight also a wing leveler function is active if the roll angle is less then 2 degrees [3].

3.2 ATTHeS In-Flight Simulator

A description of the ATTHeS in-flight simulator and its capabilities is given in [2]. The research vehicle is based on a BO 105 helicopter (Fig. 3). The next generation of helicopters are required to fly high pilot gain, high bandwidth, and high precision flight tasks, which have to be performed in a helicopter airborne simulator, too. The capability to cover the required range of dynamic response behavior is essentially limited by the characteristics of the helicopter being the host for the in-flight simulation. The high control power and the quick initial response on pilot's inputs of helicopters with a hingeless rotor are excellent prerequisites. Correspondingly, the BO 105 helicopter is well suited to be a host for an in-flight simulator. The high level of interaxis coupling and the high order response induced by the rotor system complicate the design of a full authority digital flight control system which is needed for a capable in-flight simulator.

Fig. 3 DLR In-Flight Simulator BO 105 ATTHeS

The testbed is equipped with a full authority non-redundant fly-by-wire control system for the main rotor and a fly-by-light (FBL) control system for the tail rotor. The test helicopter requires a two-men crew, consisting of a simulation pilot and a safety pilot. The safety pilot is provided with the standard mechanical link to the rotor controls whereas the simulation pilot's controllers are linked electrically/optically to the rotor controls. The FBW/L actuator inputs, which are commanded by the simulation pilot and/or the flight control system, are mechanically fed back to the safety pilot's controllers. With this function, the safety pilot is enabled to monitor the rotor control inputs. This is an important safety aspect, because the

safety pilot can evaluate, whether the inputs are adequate to the flight task. The safety pilot can disengage the FBW/L control system by switching off the FBW/L system or by overriding the control actuators. In addition, an automatic safety system is installed, monitoring the hub and lag bending moments of the main rotor. The testbed can be flown in three modes:

1. The FBW/L disengaged mode, where the safety pilot has the exclusive control
2. The 1:1 FBW/L mode, where the simulation pilot has the full authority to fly the basic helicopter
3. The simulation mode, where the simulation pilot is flying a simulated helicopter system with full authority

In the 1:1 FBW/L and the simulation mode the flight envelope is restricted to 50 ft above ground in hover and 100 ft above ground in forward flight.

To incorporate the digital control system for in-flight simulation purposes, an onboard computer and a data acquisition system have been installed. In the specifications for the design the following system conditions and requirements have been considered:

- Limited space is available in the helicopter.
- Software modifications in the control system must be accomplished in a host computer on the ground.
- A system simulation facility which is compatible to the onboard system is needed to check any software modifications before going into flight.
- The onboard system tasks, the control system, and the evaluation of the control system performance have to be clearly separated.
- The flight tests have to be observed and managed from a ground station.

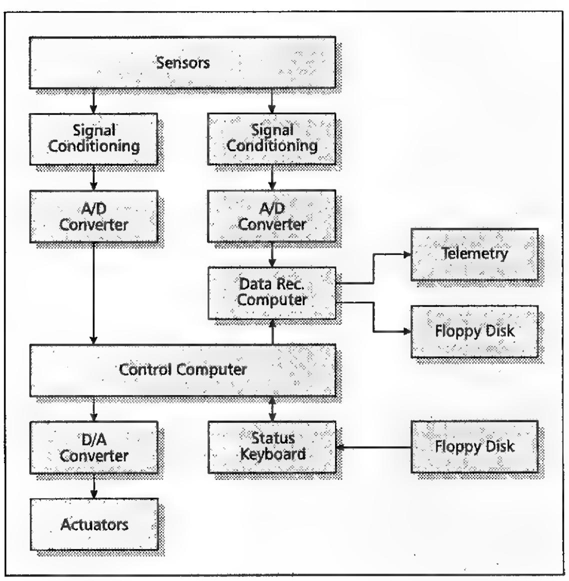

Fig. 4 Structure of ATTHeS Onboard System

Fig. 4 shows in a block diagram the onboard system. Two PDP 11 computers, ruggedized for operation in the airborne environment, are installed. The data recording task and the control system task are assigned to the computers, which allow a largely autonomous treatment of the data streams needed for the control laws and needed for the data recording for the control system performance evaluation.

The simulation pilot's inputs and the state variables, which are used in the control laws, are obtained directly from the preconditioned sensor signals with a 16 channel A/D converter. A sample rate of 25 Hz is realized. After the initialization the control system is held in the trim position. The control system starts, when the simulation pilot switches on the control status and the computer generates a subcycle of 1/5 of the frame time (8 msec). The subcycle allows refreshing the FBW/L actuator's inputs in a lower time frame than the sampling frame. For the implemented explicit model following control system, which is described in the next paragraph, this refreshing time is assessed with 16 msec. The overall computation time for the commanded model and the control laws is 13 msec. All data regarding cycle times and the measured test data included in this paper are related to a PDP 11/73 control computer. This control computer is now replaced by a PDP 11/93, which reduces the sampling and computational time to half the values.

The data recording computer is equipped with a 64 channel A/D converter. All sensor signals are sampled with a frequency of 100 Hz. A sampling frequency, significantly higher than the control computer sampling frequency, has been specified to achieve a more precise assessment of the overall system performance. Both computers are linked by a dual port memory. The measured signals, which are used in the control computer, and the signals, which are calculated in the control computer, are transmitted via the dual port memory for recording. The data are recorded onboard on a floppy disk. In addition, the data are transmitted to the telemetry. The telemetry data are only used for quicklook purposes in the ground station. The ground station also contains a host computer, which is compatible to the control system computer. Any modifications of the software code including changes of the control laws and the command model parameters are first performed in this host computer on the ground and then transferred to the onboard computers via floppy disk.

3.3 Ground-Based System Simulators

The real-time simulation of the in-flight simulators on ground is an important tool. The structures of both the ATTAS and the ATTHeS ground-based simulators are shown in Fig. 5.

The ATTAS Simulator [3] simulates the a/c as good as possible without motion cue and a visual system. The onboard data-processing system consists, as in the real a/c, of MIL-specified computers. An original ATTAS-cockpit is part of the simulator.

The VFW 614 ATTAS is simulated in real-time on an Applied Dynamics AD10. The programming language on this multiprocessor system is MPS10. The necessary interface between digital and analog world is a VME-Bus system [6]. The main task of the VME-computer is to transport the simulation data between the a/c real-time simulation on the AD10 and the *onboard* data-processing system via hardware interfaces. It is designed to cover the special needs of the *onboard* MIL-specified computer network. The MIL-Bus is a bi-directional interface-bus transporting input- and output-data.

The VME-Bus computer contains two CPU-boards with 68020 processors equipped with 1 Mbyte local memory each, communicating via 64 kbytes shared memory. One processor performs the analog in- and output, the other computes the rest of the interfacing including the user interface.

The operating system PDOS is in use for developing and running the software on the interface computers. The programming language is C.

Corresponding to the ATTAS simulator described above an ATTHeS simulator has been developed. The ATTHeS system simulation tool permits the examination of the real time software. The basic helicopter and the actuating system are represented by a non-linear model. The onboard computer system has been duplicated in the ground system simulation. This tool

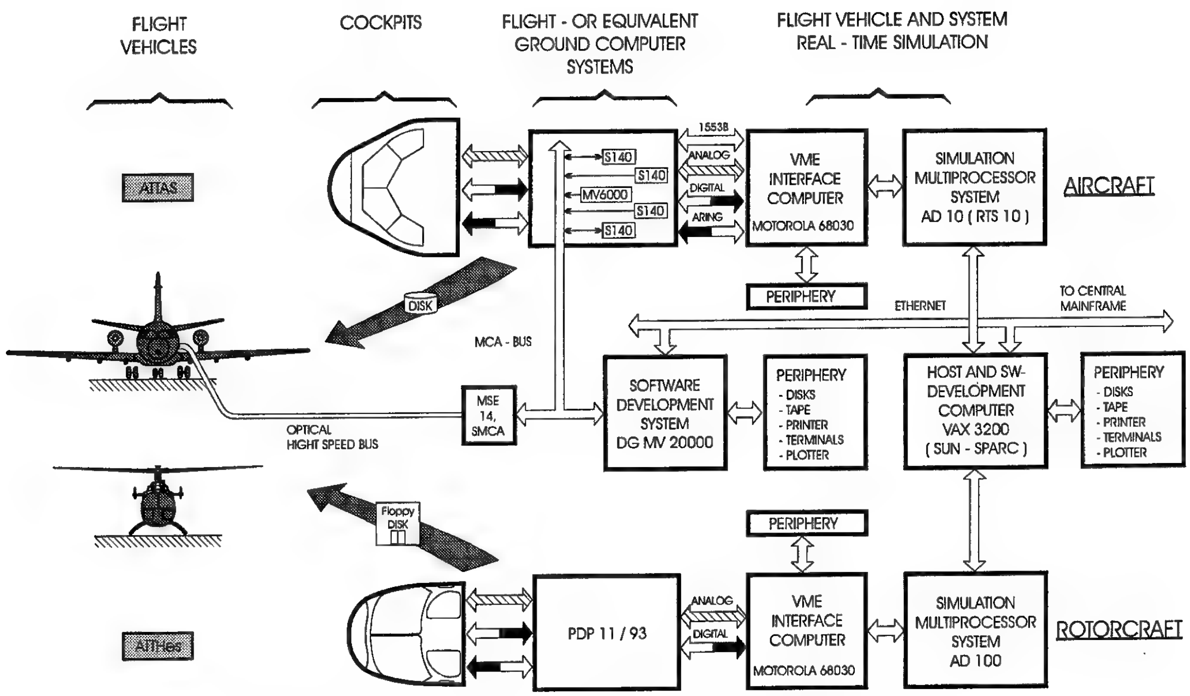

Fig. 5 Structure of ATTAS and ATTHeS Ground-based System Simulators

allows a compatible hardware and software in the loop testing before an implementation in the flying ATTHeS helicopter.

Every experiment flown on both in-flight simulators can be checked on the ground. The scientist is able to validate his software and obtain first results. Another important fact is to train the pilots and find out their opinions before going airborne. The ground simulation reduces the costs and also a lot of development risks. The standard of the ground-based real-time simulators allows the realization of typical experiment concerning simulation technique.

4 ATTAS FLIGHT TEST RESULTS

4.1 SCARLET

Within the SCARLET project (**S**aturated **C**ommand **A**nd **R**ate **L**imited **E**levator **T**ime delay) the influence of actuator rate saturation on the handling qualities of modern fly-by-wire aircraft has been examined. The aim was to develop an alternate control scheme to eliminate the time delay between actuator command and reaction.

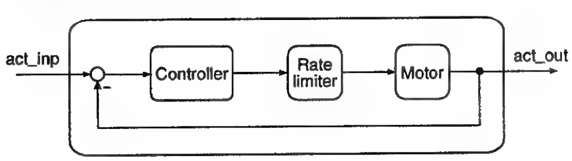

Fig. 6 Rate Limited Actuator

Actuator rate saturation can lead to a significant time delay between the actuator input and the actuator output. This time delay arises due to the interaction of two rate limited elements in the control system: the actuator itself, and the *command* to the actuator (actuator input). The actuator is rate limited due to 'real-world' effects.

Fig. 6 depicts a typical actuator consisting of a motor or hydraulic booster and a controller. The error between the actuator command and the output is calculated by the controller and used to drive the motor. The motor, however, can only respond with a limited rate due to constraints in electric current or hydraulic flow. The actuator command, on the other hand, is intentionally limited, either by a software rate limiter somewhere in the control system, or simply by the pilot, if the stick is moved with a limited rate.

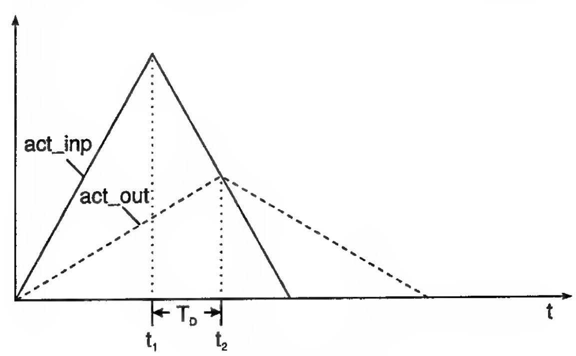

Fig. 7 Time Delay

Consider now a situation in which the rate limited command is faster than the actuator, as shown in Fig. 7. In the first time period ($0 < t < t_1$), the actuator strives to reach the command with its maximum rate; however, a discrepancy will develop between the magnitudes of the command and the output due to the difference in rate limits. When the command then changes direction at t_1, its magnitude is greater than that of the actuator output, and therefore the command begins to move *into* the direction of the output while the actuator continues in its *original* direction as it tries to meet the command. Only when the magnitudes of the two signals meet at t_2 will the actuator finally change direction to follow the command. The time period between the reversal of the command and the reversal of the actuator output is the time delay T_D.

The time delay could be eliminated if the actuator reversal occurred at the same point as the command reversal, as shown in Fig. 8.

Therefore, a solution is suggested through the following Alternate Control Scheme (ACS):

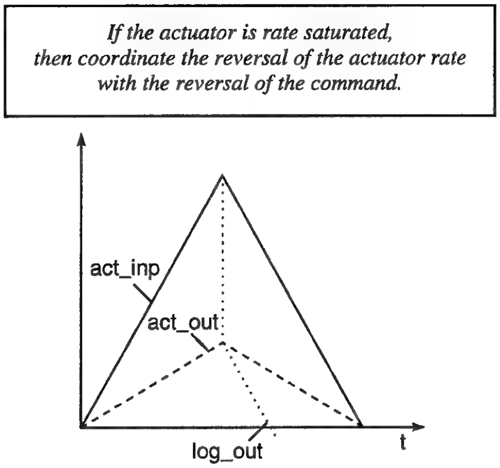

Fig. 8 Time Delay Elimination

The ACS can be implemented through the use of a logic block placed directly before the actuator in the control loop, as depicted in Fig. 9.

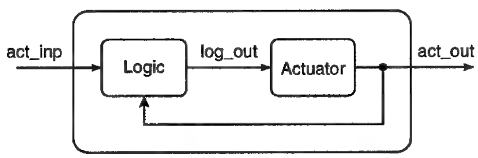

Fig. 9 Smart Actuator

The actuator command from the control system is fed into the logic block. The logic then determines whether ACS is required based on information about the command and the actual actuator output. When ACS is to be activated, the logic block provides an output signal which serves as a new actuator input. This modified input is calculated to produce the desired actuator output. If ACS is not required, then the logic block simply passes on the normal actuator command as input to the actuator.

This process is clearly illustrated in Fig. 8. In the first time period the command demands more than the actuator can achieve, such that as before a discrepancy develops between the magnitudes of the signals. However, when the command changes direction, ACS switches on and produces the output shown, which serves as the *new* actuator input. The actuator now strives to follow the logic output and thus changes direction *immediately*, and therefore the time delay disappears. The basic design philosophy is that when conditions are right for the occurrence of the time delay (i.e. the actuator is saturated), then the normal control system structure is bypassed, and the information about the command reversal is passed *directly* to the actuator. Thus the time delay is eliminated.

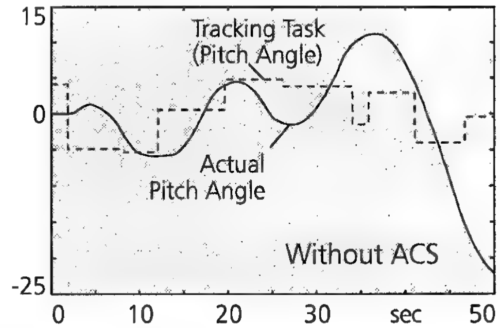

Fig. 10 SCARLET Flight Test Results without ACS

Fig. 10 shows an ATTAS flight experiment in which the maximum elevator rate has been artificially limited to 0.46°/sec. Without the alternate control scheme the above mentioned time delays lead to an uncontrollable, PIO-like situation. The safety pilot had to take the wheel.

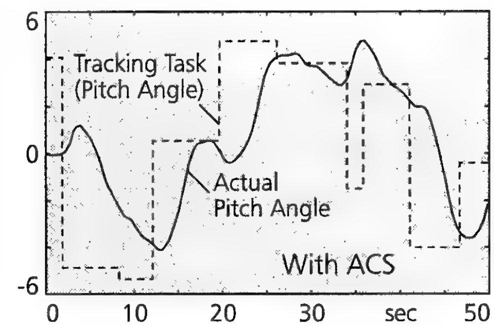

Fig. 11 SCARLET Flight Test Results with ACS

With the alternate control scheme no time delays and therefore no pilot induced oscillations occur (Fig. 11). Even though the pilot has some problems to fulfill his task because of the extreme rate limit, he is permanently in control of the aircraft.

4.2 Reconfiguration

Control system reconfiguration becomes necessary with the occurrence of failures or damages in the aircraft actuator system (elevator, aileron, rudder, ...). The control system has to be adapted in order to have intact actuators take over the tasks of the impaired ones (Fig. 12). The inherent redundancy in most modern actuator systems is the main prerequisite for such a substitution. Damage of the elevator for example can be compensated at least partly by the stabilizer; rudder and asymmetrical thrust both produce a yawing moment. If there is no possibility to fulfill the pilot's commands because of the

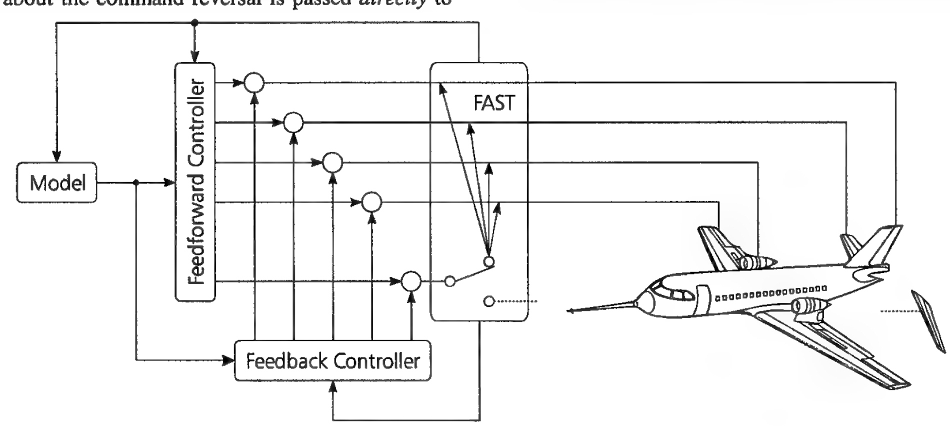

Fig. 12 FAST (Fault Accommodation by Structure Tuning)

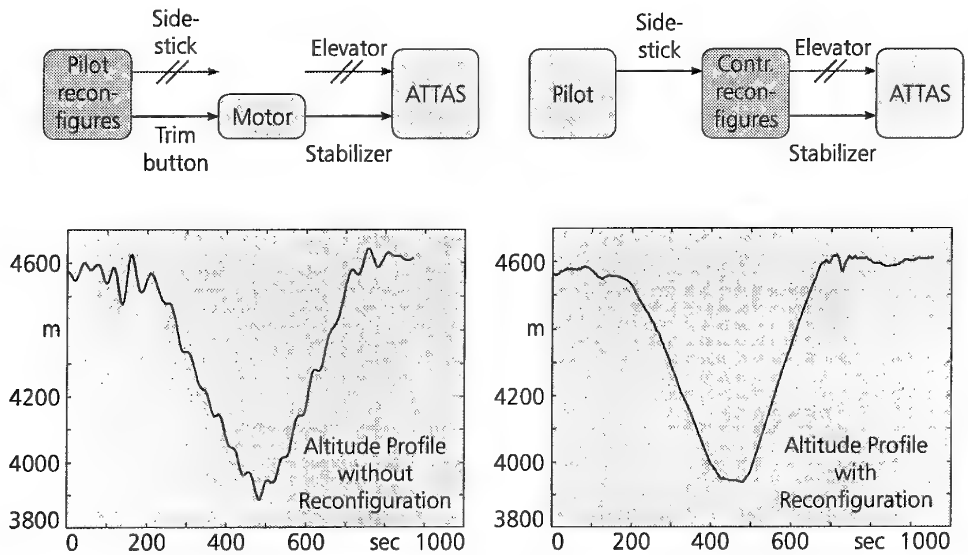

Fig. 13 FAST Flight Test Results

degradation, the pilot's demands are translated into suitable commands that can be realized.

4.2.1 FAST

FAST (Fault Accommodation by Structure Tuning) is a new control system reconfiguration concept for a contemporary fly-by-wire aircraft. DLR's in-flight simulator ATTAS is used as test bed for the validation of the concept.

The controller consists of a feedforward and a feedback part (Fig. 12). The reconfiguration of the feedforward block represents the main task. Besides knowledge based reconfiguration for that part of the fault that can be quantitatively gauged, automatic control system parameter adaptation by means of robust genetic algorithms (see chapter 4.2.2) can take care of those fault impacts that have not been numerically determined.

The fault is supposed to be known. It has to be determined by a fault detection routine. FAST itself consists of two successive steps. At first the qualitative and quantitative information about the fault is used to restructure the control system. This first part of the reconfiguration has to be done immediately after the fault information is available, in order to ensure continuous stability and maneuverability of the aircraft. The second reconfiguration task can then be performed in a much broader schedule: An automatic parameter adaptation routine can be applied to take care of those impacts of the fault that could not be quantitatively gauged. Such an adaptation basically involves an optimization to alter the parameters of the control system via a certain strategy within predefined limits in order to maximize control performance. Since in most cases this optimization is only a “nice to have”-feature, the convergence speed of this procedure is not as important as in the case of the preceding immediate knowledge based reconfiguration. Robustness, which in this context is the ability of the optimization algorithm to find and keep the global optimum, is of much more concern.

Fig. 13 shows the results of two ATTAS flight experiments, during which the elevator was disengaged. In the first experiment the pilot was asked to use the stabilizer trim button instead of the longitudinal stick to cover a predefined altitude profile. He encounters severe problems stabilizing the phugoid mode with the slow stabilizer (Fig. 13 left).

After a control system reconfiguration in the second experiment the pilot can use the stick and the old control law to command the aircraft. The reconfigured control system transforms his command, that had formerly been sent to the intact elevator, into equivalent commands for the stabilizer. By this, the reconfiguration enables the pilot to fulfill his task much more precisely.(Fig. 13 right).

4.2.2 GRACE

Negative effects of actuator faults on the operation of a flight control system unable to be taken into account by fault identification and knowledge based reconfiguration can be minimized during an adaptation period. The analyzed flight control system contains an explicit model following control structure with model, feedforward, feedback, and the basic aircraft process (Fig. 14).

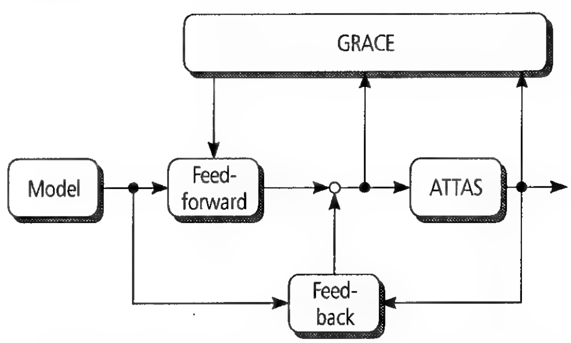

Fig. 14 GRACE (Genetic Reconfiguration Algorithm for Control System Enhancement)

In order not to end up with unnecessary stability problems, only the feedforward parameters are adjusted by the adaptation algorithm. The optimization technique used for the parameter adaptation is a genetic algorithm applying the principles of natural evolution, i.e.

- Selection,
- Recombination, and
- Mutation,

to technical problems. Such an algorithm produces near-optimal solutions very reliably and was successfully tested both in simulation and flight experiment. The result of the conducted flight experiment demonstrates a significant reduction of the control error after adjusting the feedforward pa-

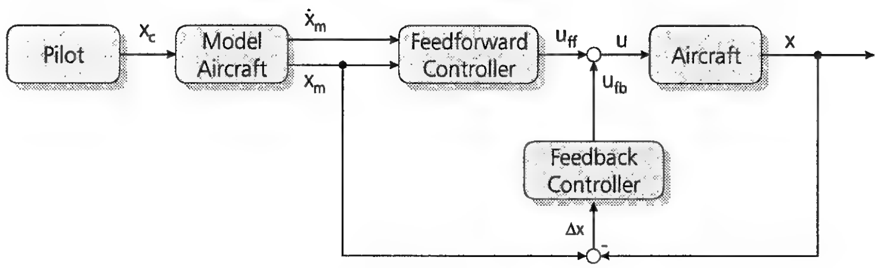

Fig. 15 IFS Model Following Control Concept

rameters caused by an unpredicted elevator effectiveness failure of fifty percent.

4.3 A3XX In-Flight Simulation

The in-flight simulation available on ATTAS is based on an explicit model following control system (Fig. 15). The first of two essential parts of this system is a feedforward controller, which represents the inverse dynamics of the host a/c. The second part is a feedback controller with proportional and integral elements.

The most recent application of this system has been the airborne simulation of the Airbus A3XX transport a/c, which is presently under development. The model is based on preliminary data, is unaugmented and has no elastical degrees of freedom. A typical flight-test result is illustrated in Fig. 16.

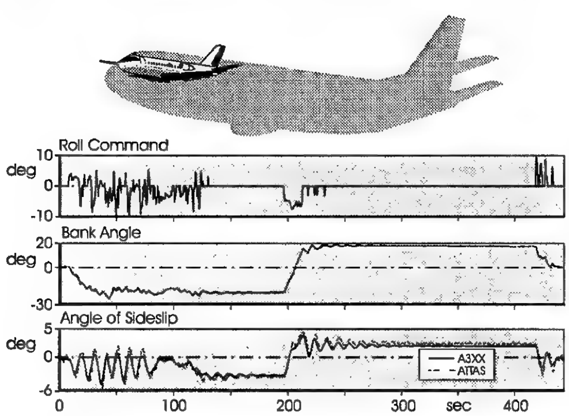

Fig. 16 A3XX In-Flight Simulation

The pilot had the task to perform a turn reversal. With his aileron inputs he excited the Dutch roll motion. The sidestick commands illustrate, that at first he had problems to perform the task because of the oscillation. The match of the flight states (bank angle and angle of sideslip) of model and ATTAS indicate a sufficient performance of the model following system.

4.4 SAFIR

Within the SAFIR project (Small Airliner Flight-Control-Laws Investigation and Refinement) flight control laws for a future 100 seater transport type aircraft have been investigated which were designed by the *Daimler-Benz Aerospace Airbus*. The aim of this contract work was the validation, demonstration and valuation of the flight control laws by a flight test program performed on the DLR testbed ATTAS. Especially flying qualities and flight envelope protections were analyzed.

During the first flight test campaign (SAFIR 1) the flight control law package of the *Daimler-Benz Aerospace Airbus* was implemented on the *Experimental and Control Computer* of ATTAS. It was coupled with the ATTAS data processing system by an individual interface program for the control of the different experimental functions [9]. Numerical codes and supporting software elements were developed to generate those specific control law input signals required by the flight control laws and not provided by the comprehensive ATTAS standard sensor and measurement system (Fig. 17). The final adjustment of the flight control laws, the adaptation to the ATTAS real world system, the experimental check out, and the pilot's flight test training were performed using the ground based ATTAS system simulator [5].

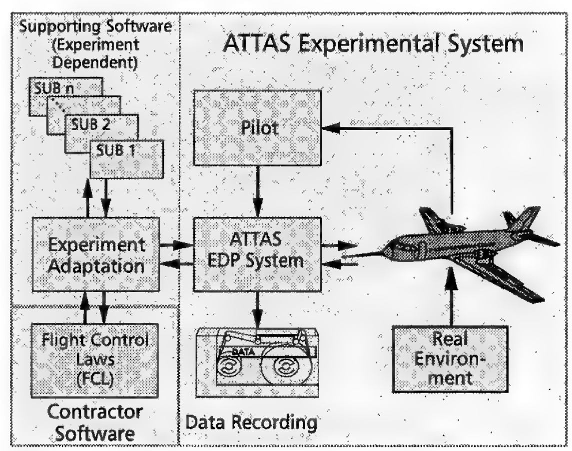

Fig. 17 SAFIR Flight Test Concept on ATTAS

The flight control laws include normal laws (full controlled a/c), direct laws (direct links between cockpit control devices and control surfaces), and flight envelope protections which were investigated during the flight tests:

- Pitch axis
  - n_z-law
  - Turn compensation
- Roll axis
  - Roll rate command bank angle hold law
- Yaw axis
  - Rudder command
  - Turn coordination
  - Yaw damper
  - Compensation of non-symmetrical thrust
- Protections
  - Pitch attitude protection
  - Bank angle protection
  - High angle of attack and high speed protection
  - n_z protection

A typical flight test result is given in Fig. 18. It shows the time histories of a left hand turn flight maneuver. Roll normal law is a roll rate command/bank angle hold law. The roll rate command is proportional to side stick deflection and limited to $|p| < 15°/s$. Bank angle hold is provided up to $|\phi| = 33°$ with automatic turn compensation. This allows turns to be flown

without manual pitch inputs. For bank angles $|\phi| > 33°$ spiral stability is introduced. The maximum bank angle in ATTAS flight tests was limited to $|\phi| < 45°$ ($|\phi| = 30°$ in AOA Protection and High Speed Protection). Turn compensation is reduced in accordance with the bank angle so that pilot action for pitch control is required [10]. The effect of the bank angle protection is illustrated in Fig. 18. The defined maximum bank angle is not exceeded although full side stick deflection is commanded. After stick release to neutral position the bank angle of $|\phi| = 33°$ is established.

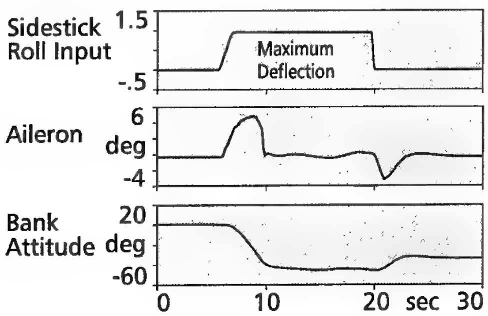

Fig. 18 Bank Angle Protection (Flight Test Results)

The pitch normal law is a load factor law with automatic trim function. At low speed load factor is blended with pitch rate. A load factor limitation allows adequate maneuvering without risk of structural overload. If a predefined angle of attack is exceeded (α_{prot}), an angle of attack command law becomes active, protecting the aircraft against stall [10]. Fig. 19 gives the flight test results of the angle of attack protection which prevents the aircraft from pitching to excessive high angles-of-attack ($\alpha < \alpha_{lim}$) even for full aft stick deflection. After stick release to neutral position the angle of attack is lowered and α_{lim} is established.

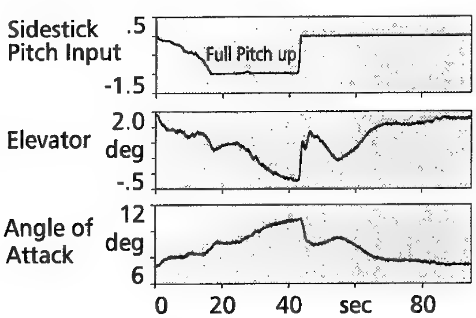

Fig. 19 Angle of Attack Protection (Flight Test Results)

Pilots judged the in-flight results to be consistent with the simulator results. The transition from α-command to n_z-command mode was found to be very sensitive to pitch rate and load factor cues and can therefore only be optimized by means of flight testing [10].

For the handling qualities investigations a simple but powerful flight maneuver was designed containing seven different segments (Fig. 20). From this SAFIR maneuver the pilots derived COOPER-HARPER ratings and general comments in a questionnaire.

The outcome of results for the handling qualities is illustrated by Fig. 21 and Fig. 22. Both figures show the effect of the roll rate command/bank angle hold control law with full turn compensation (for turns with bank angles of $|\phi| < 33°$) compared with turns where pilot action for bank and pitch control is required (for bank angles of $|\phi| > 33°$). Although for this principle study of SAFIR the control laws were adapted but not optimized the quality of the FCL's for normal operation ($|\phi| < 33°$) was generally rated as Level 1. Leaving the flight envelope of normal operation ($|\phi| > 33°$) the design of the FCL's demand more pilot activity to increase his situation awareness. This intended effect causes the degradation of pilot ratings.

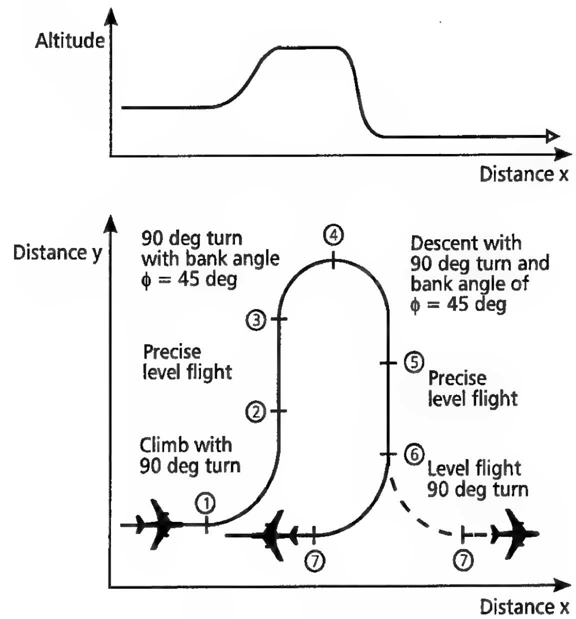

Fig. 20 SAFIR Maneuver

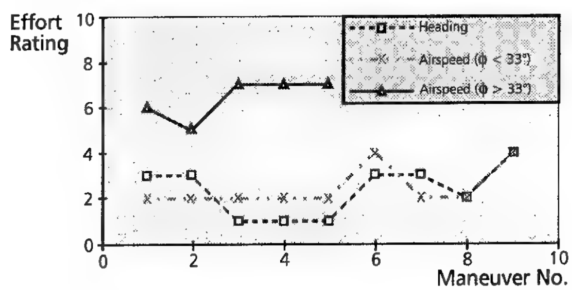

Fig. 21 Effort Ratings for Heading and Airspeed Control

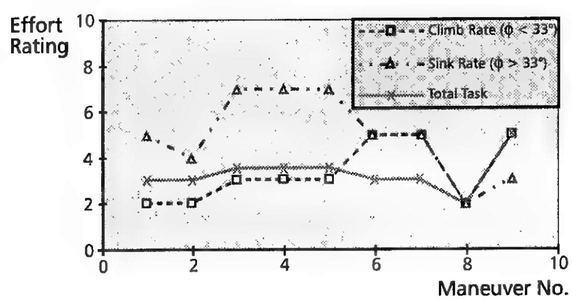

Fig. 22 Effort Ratings for Vertical Speed Control

Right now the SAFIR 2 project is successfully running. This flight test program is directed to the investigation of system aspects such as

- Dissimilar software,
- Data consolidation, and
- FCL degradation (direct laws).

To carry out these investigations a flight-worthy HARRIS Night Hawk 4401 computer has been connected to the ATTAS EDP-System (Fig. 23). The computer calculates the flight control laws quasi-parallel using two different codes (FORTRAN, ADA).

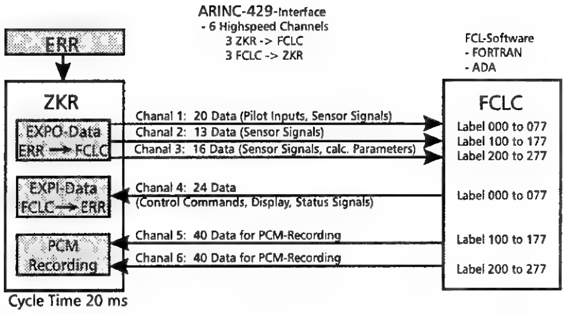

Fig. 23 Integration of the Flight Control Law Computer

5 ATTHES FLIGHT TEST RESULTS

5.1 Bandwidth Criteria Evaluation

The introduction of high authority flight control systems in rotorcraft created the need for new helicopter handling qualities requirements. In response to this, a new helicopter handling qualities specification was developed under the leadership of the US Army and published as Aeronautical Design Standard 33 (ADS 33) [11]. In a new bandwidth and phase delay criteria format, requirements are specified relating to the rotorcraft's ability to perform small amplitude and high pilot gain tasks such as ground and air tracking, slope landing, etc. The bandwidth criterion is an application of the pilot crossover model. It provides a measure of the maximum frequency a pure gain pilot can achieve without closed loop instability and without any tendency of pilot induced oscillations. Low bandwidth of a system indicates the need of pilot equalization during high frequency tasks. The helicopter phase delay describes how quickly the phase lag increases beyond the neutral stability frequency. When the pilot has to control above the neutral stability frequency, a significant amount of pilot lead compensation is required which increases the pilot's workload and deteriorates the handling qualities evaluation. For the design of actively controlled helicopters, bandwidth and phase delay are two important design parameters. Bandwidth is a basic parameter for control system design. Phase delay can be directly related to the equivalent time delay of a system and is composed of the contributions of the basic helicopter and of portions produced by a control system.

Since its introduction, research has been conducted to extend the data base on which the ADS 33 criteria are based on. A review of the data base used for the definition of the ADS 33 bandwidth requirements showed that these were primarily obtained from ground-based simulations and flight tests with low bandwidth variable stability rotorcraft. The ADS requirements allow increasing phase delays with increasing bandwidth. Singular data points achieved in previous tests with an early control system design for BO 105 ATTHeS with equivalent time delays of more than 200 msec showed significant discrepancies with the ADS requirements. Although the data points were clearly within the ADS Level 1 limits the pilots rated poor handling qualities in high gain piloting tasks. Recognizing these discrepancies an activity was started to extend the data base and to verify the ADS level boundaries for the roll axis in forward flight.

The variable stability BO 105 ATTHeS was used to investigate the effects of varied bandwidth and phase delay for a high gain slalom tracking task [12]. The capabilities of ATTHeS achieved by the high bandwidth characteristics of the basic BO 105 helicopter and the specifically designed explicit model following control system were well suited for these tests. Two response characteristics were implemented: a first order rate command (RC) and a second order attitude command (AC) system. These command modes were defined for roll and pitch axes. Rate of climb response and sideslip command were defined for the vertical and pedal axes. The responses to the control inputs were fully decoupled, except for an altitude hold term. The response characteristics were varied in bandwidth and time delay by a variation of the primary experimental variables roll damping and time delay for the RC and natural frequency and time delay for the AC (damping ratio was held constant at 0.7). With these variables, bandwidth could be varied between 1.45 rad/sec and 4.3 rad/sec. Starting with the ATTHeS inherent equivalent time delay in roll axis of 110 msec, time delays were added in steps of 40 msec up to 160 msec resulting in overall system phase delays between 80 msec and 205 msec.

Fig. 24 shows the data points from the flight tests in the ADS format. The data point of the basic BO 105 is added. The test results can be summarized:

1. A high degree of consistency between the rate and the attitude command configurations exists. This confirms not only the independence of the bandwidth and phase delay criterion with regard to the response type, but also illustrates the appropriateness of the slalom tracking task used for the investigation and demonstrates the suitability of ATTHeS to cover also high bandwidth configurations with good fidelity.
2. The shape of the boundaries recommended by the test data are significantly different from the ADS 33 requirements. The phase delays are limited for Level 1 at about 0.1 msec and for Level 2 at about 0.17 msec.

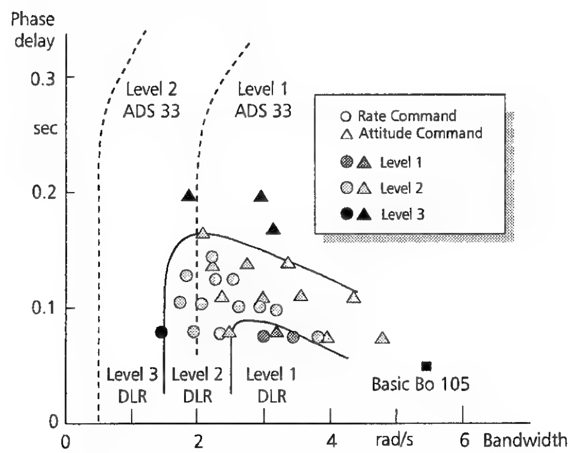

Fig. 24 Flight Test Data of the Bandwidth Study

In the updated ADS 33D version, these modified requirements are accepted as roll axis requirements for target acquisition and tracking tasks in hover and air combat tasks in forward flight.

5.2 Rotor Decoupling Study

Typical high agility, high bandwidth helicopters, like the BO 105, exhibit severe pitch-roll coupling. This coupling is produced by the stiff rotor system and the large hinge offsets of the blades which are required to generate the large rotor moments especially needed for the agility and the responsiveness in high gain piloting tasks. High authority control systems can provide an active decoupling of the helicopter to reduce the pilot workload to an adequate level. Whether a control system should be designed to eliminate all coupling is questionable and will be balanced by the operational needs, the technological effort for the control system, and the costs. In addition, an augmented helicopter must be controllable after a control system failure, too.

In ADS 33 the maximum allowable levels of pitch-roll coupling are specified in a time domain format. The criteria defines ratios of peak coupling responses to peak on-axis responses to given cyclic inputs which are θ_{pk}/ϕ for pitch-due-to-roll and ϕ_{pk}/θ for roll-due-to-pitch. By defining a 4 sec segment for the measurement of the ratios, the criterion primarily considers the mid to long term effects. However, in a high gain pilot task the mid to long term coupling responses can be more easily compensated by the pilots and therefore may secondarily influence the pilot workload. Whereas the suppression of the short term coupling response will drastically increase the pilot workload. Furthermore, the short term effects are particularly important for the control system design and will lead the effort in the design. Long term coupling can be easily eliminated by a simple feedback control system.

In cooperation with the US Army a research program was conducted to establish a more comprehensive crosscoupling data base. The in-flight simulator ATTHeS was used to investigate the effects of different types of coupling with a strong emphasis on the inclusion of coupling types which are representative for highly augmented helicopters [13]. The implemented model consisted of two parts: An uncoupled baseline model which was evaluated as Level 1 and a pitch-roll crosscoupling model. The baseline model was a first order rate command with a roll axis bandwidth and phase delay of 3.44 rad/sec and 77 msec, respectively and with a pitch axis bandwidth and phase delay of 2 rad/sec and 114 msec, respectively. Three different types of crosscoupling were realized and varied in magnitude and dynamics:

1. Control coupling
2. Rate coupling
3. Washed-out coupling

Control and rate coupling represent the coupling behavior of an unaugmented helicopter. In an actively controlled helicopter, any off-axis responses from control or rate coupling will be reduced to zero by a feedback system which can be characterized by a washed-out type response.

An intensive analysis of the pilot control strategy to compensate the coupling responses gained the fundamental understanding of how coupling affects the pilot workload. In the tracking phases of the roll axis slalom task the pilots used a feedback control strategy. While acting as a feedback system, the pilots primarily controlled the on-axis roll task and used spare capacity to remove the unwanted coupling. As coupling increased more attention was needed for the off-axis control. This resulted in poorer task performance, lower lateral input power, and poorer handling qualities ratings. With increasing coupling response in the pitch axis, the pilots increased the longitudinal input power and used higher frequencies in the longitudinal control. For severe coupling cases, longitudinal input activity shifted to the bandwidth and neutral stability frequency of pitch axis. For some of the most severe coupling cases, input activity above the neutral stability frequency was observed resulting in mild pilot induced pitch oscillations. This frequency dependent feedback strategy accounts for the inconsistencies between the control/rate and the washed-out coupling when using a criterion format in the time domain. The ability of the pilot to suppress coupling will depend largely on the system capabilities of the axis he has to use to compensate coupling. Parameters which are a function of the frequency characteristics of the compensatory axis yield an adequate correlation with the pilot ratings. In Fig. 25 the relative coupling amplitudes at the bandwidth frequencies of the compensatory axis are crossplotted.

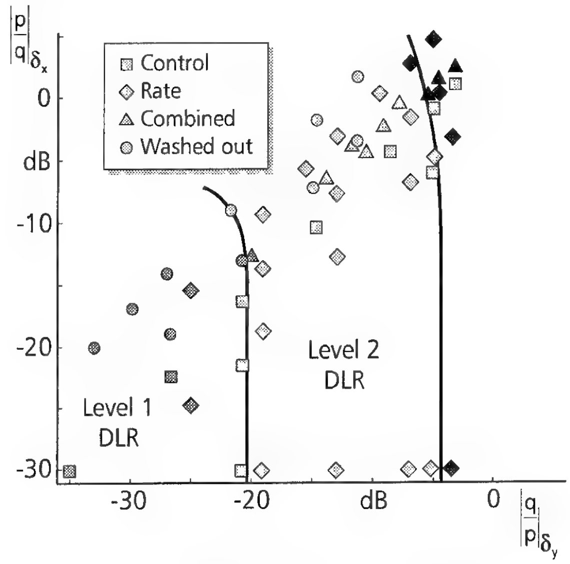

Fig. 25 Flight Test Data of the Coupling Study

A two sided format allows to consider the effects of the individual and combined roll-to-pitch and pitch-to-roll couplings in one diagram. An additional benefit of the frequency domain criteria is that the required data can be obtained from the bandwidth tests and analysis, thus eliminating the need for additional compliance test data.

5.3 Lynx In-Flight Simulation

For the purpose of a rotorcraft simulation in flight a special simulation model to be followed has been developed for ATTHeS. This real-time command model consists of a linear 9 DOF model which is extended with nonlinear terms for an improved simulation fidelity [14]. Either from flight test data or from runs of a generic simulation program the model dynamic matrix **A** and the model control matrix **B** are calculated using system identification procedures [15].

The necessary nonlinear terms for coordinated turns, gravity, changes of flight path, and the Euler equations are programmed explicitly. In addition, a four axes stability and control augmentation system (SCAS) for the simulated helicopter can be incorporated. The SCAS can be engaged or disengaged during flight with software switches. For the investigation of SCAS failures, several failure situations with changeable degradation and reconfiguration blending can be simulated. When adequate models of a helicopter are available, the helicopter simulation with ATTHeS can be used in the approach to develop and adapt a control system to the helicopter dynamics. The evaluation of software and hardware components in the integrated system, with the pilot-in-the-loop, and in a real flight environment will support the design approach and will drastically reduce the risk of a system development.

The in-flight simulation of the Lynx helicopter serves as an example to describe the simulation capability. The Lynx helicopter has some differences in the response characteristics compared to the basic BO 105, for example some couplings are opposite to the corresponding couplings of the BO 105.

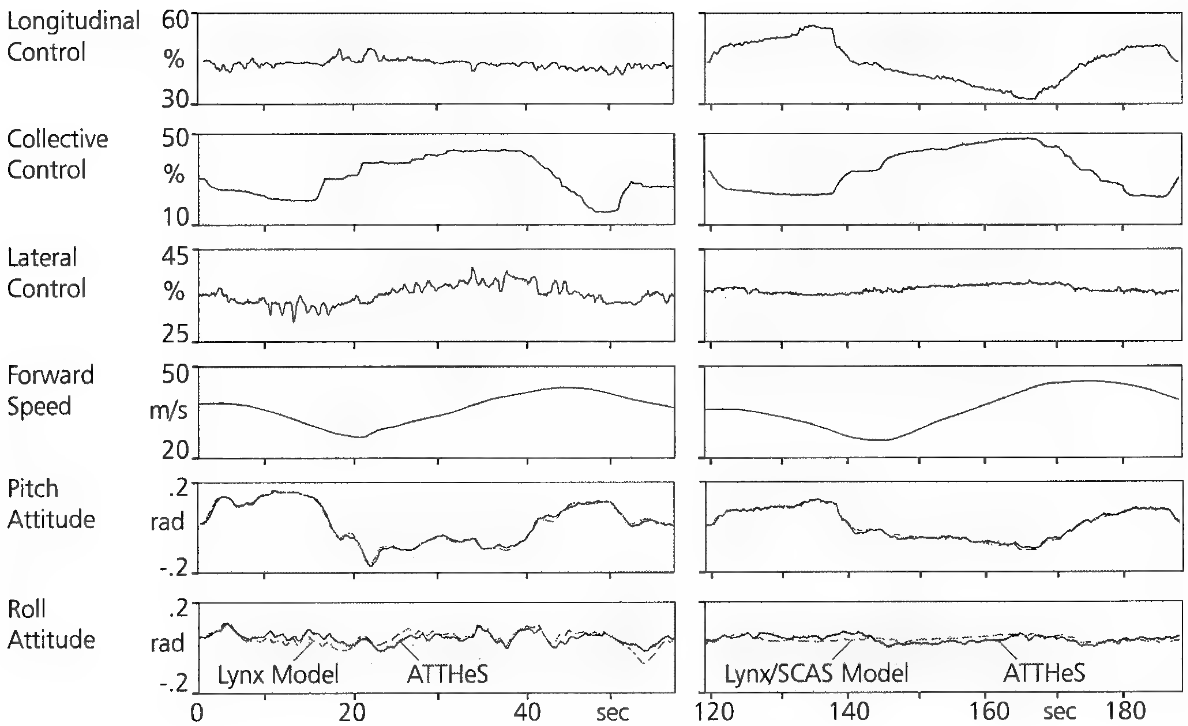

Fig. 26 Simulation of Lynx Helicopter Dynamics

Fig. 26 demonstrates the simulation fidelity of the in-flight simulator ATTHeS. The left diagram provides flight test data of the simulated basic Lynx without a SCAS in a speed variation maneuver. The time histories in the right diagram show test data with a SCAS specifically designed for the simulated helicopter. Experienced Lynx pilots who have flown the tests commented the compatibility with the operational Lynx helicopter as very satisfactory.

5.4 Vision Based Hovering Experiment

The demands to extend the helicopter mission profiles, i.e. that helicopters can be flown at night and in adverse weather, drives the need to design advanced control systems. Especially in hover and low speed where the helicopter is flown close to the ground, augmentation for the pilot is required to reduce the pilot's workload to an acceptable level. A special task in various mission phases is the position hold under gusty conditions over a ground fixed or moving target which could be a shipboard or lifeboat reference.

DLR has equipped ATTHeS with an innovative system for the measurement of a reference hover position. A video camera together with a sophisticated computer system for processing the optical information was used as an integrated target scanning sensor. Based on the existing model following control system of ATTHeS, the control system was modified by adding a feedback control structure for minimizing position errors [16]. For a helicopter in hover, the longitudinal and lateral accelerations can either be controlled by changing the pitch and roll attitudes or for short term corrections directly by the sideforce capability of the rotor system. The helicopter position in relation to a ground target is a second order differential equation with a nonlinear function in the attitudes. The model following control system in hover highly emphasized the stabilization of the attitude loops. For the position hold task, additional terms in the attitude loops were incorporated. These terms concern the relation between the commanded pitch and roll attitudes for the relative position errors and the corresponding velocities. The coefficients of the additional control loops were preoptimized in a non-real-time simulation. Before performing any flight tests, the position hold hardware and software had to be integrated and evaluated in the real-time ATTHeS system-simulation, which is used as the standard pre-flight test procedure.

In the flight tests the position target was presented by a black square which was mounted on the top of a car. The task of the test pilot was to fly the helicopter, which had implemented a decoupled rate command attitude hold control mode, above the target. When the target was within the range of the video camera the position hold mode was engaged by the pilot pressing a button on the MFCS keyboard. When the pilot moved the cyclic control the position hold was automatically disengaged. The position hold control system had to fly the helicopter above the target in constant altitude and with constant heading while the pilot had the hands off the controls. When the target was ground fixed the achieved position accuracy was about 1 m. To simulate a moving target, the car then drove a circle (40 m radius) with 15 km/h. With the moving target, the position errors deteriorated up to 2.5 m.

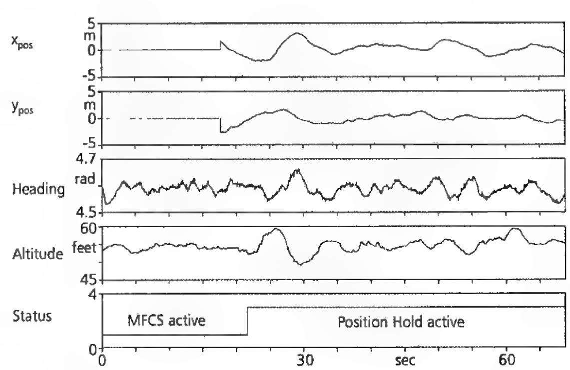

Fig. 27 Helicopter States during Autonomous Hover

Fig. 27 shows time histories of a test which was performed in a 15 kts wind condition and with gusts up to 30 kts.

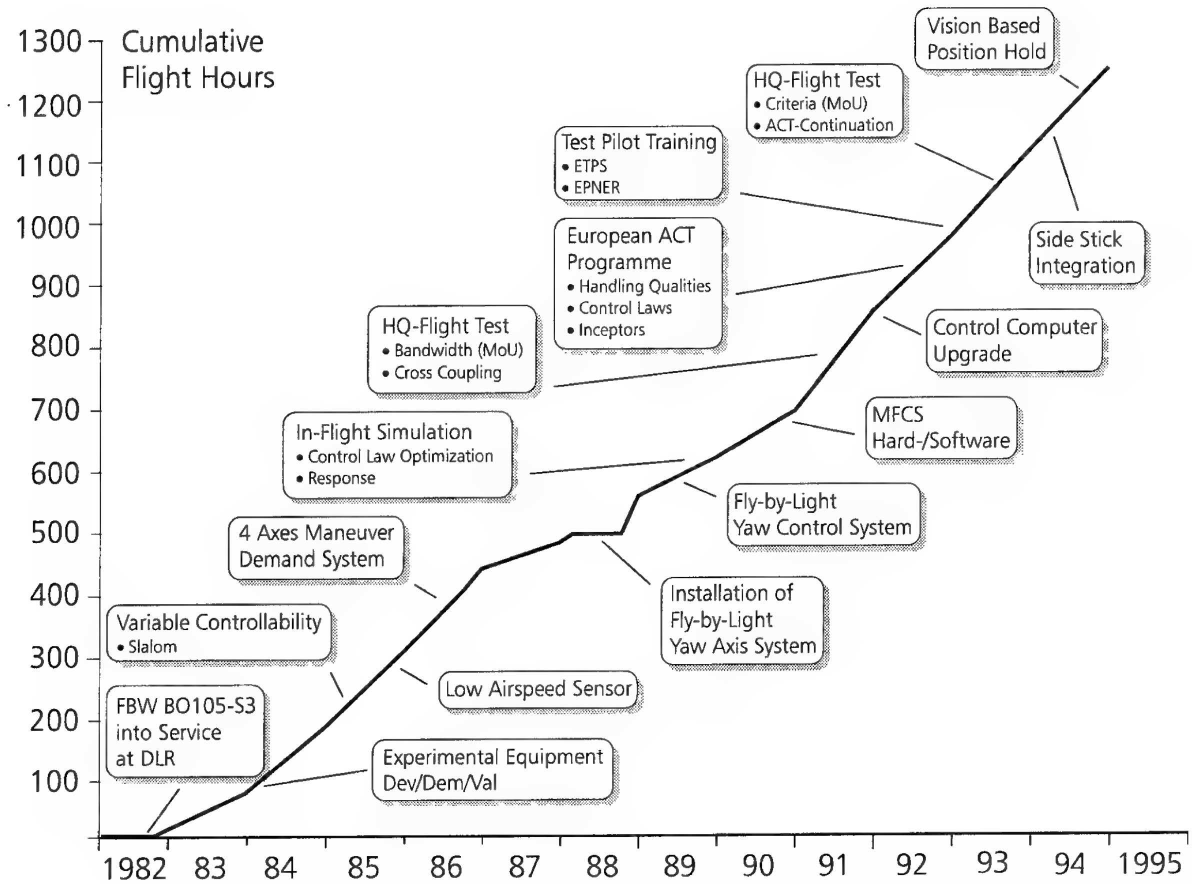

Fig. 28 ATTHeS Flight Test Statistics

5.5 Flight Test Statistics

Fig. 28 overviews the flight test activities with ATTHeS.

The fly-by-wire helicopter BO 105-S3 came into service at DLR in 1982. Since that time several flight test programs have been performed demonstrating the multipurpose capability of the airborne simulator. Beside a continuous improvement of the simulation hardware, the utilization of ATTHeS can be summarized:

- Development and improvement of the explicit model following control system
- Development of advanced control systems
- Generation of credible handling qualities data
- Test pilot training

On average, about 150 flight test hours a year demonstrate the effectiveness and applicability of the in-flight simulator ATTHeS.

6 ASPECTS OF SIMULATION FIDELITY

During the last decades the ground-based a/c simulation has become a well-known and accepted technique. It is not only in use for training purposes but also for scientific applications. The already mentioned in-flight simulation is as well known, but because of its costs it can only be found in a few centers in Germany, Russia and the USA. However, both techniques have to deal with the problem that the computer based simulation of dynamic systems has inherent deficiencies. First the in-flight simulation:

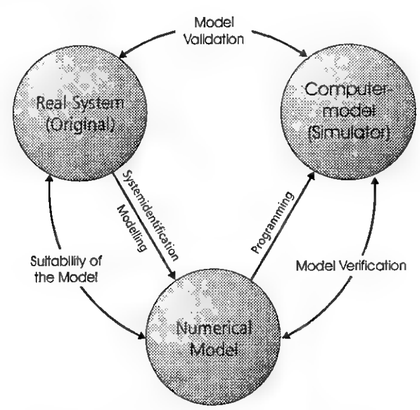

Fig. 29 Modeling of a Dynamic System

Fig. 15 illustrated two essential sources, which can be responsible for deficiencies concerning this particular simulation technique:

- *A/C model to be simulated*: Fig. 29 shows the elements, which have to be taken into account developing an a/c model:
  - *The real system*: The requirement is to reproduce particular characteristics of this system. These can be the dynamic characteristics as well as functional aspects or whatever the aim of the simulation is.
  - *The numerical model*: It contains the mathematical description of the system to be simulated. The parameters and the order of the equations are the result of an investigation with the real system as central element.

- *The system model in the computer*: The basis of this system is the algorithm of the numerical model. It has to be transferred to a higher programming language. The combination with a database describing the real system allows it to imitate the dynamic of the real system in a given quality.
- *Model following system*: The feedforward controller of the model following system is based on a flightmechanical database of the host a/c. Adequate model following can only be achieved if the database represents all dynamic characteristics of the respective flying testbed.

The second example is the motion-based flight simulator. [21] touches some typical problems these systems have:

- In the case of a fixed-based simulator there are no proprioceptive cues.
- A motion-system has physical limits and therefore some cues are more or less suppressed (e.g. only 10-15% of the real roll acceleration $\dot{p}$ are available).
- Some cues, such as the load factor n_z, are missing.
- Because of washout filtering, some cues are generated which never appear in a real airplane. The design of washout filters is still a kind of black art.
- The harmonization between a/c motion-system and visual-system dynamics is a problem area.
- The workload of the pilot in a simulator and in real flight is generally different. Investigations concerning PIO-effects, for instance, have shown this.

6.1 Model Following Fidelity Evaluation Methods

6.1.1 General Remarks

The evaluation of model following fidelity is usually based on qualitative and quantitative aspects. The more qualitative method is to plot the flight states of model a/c and host a/c in one diagram. It is then possible to see how well the two curves match. This optical check can be supported by an additional error curve, which will be shown in this section (see Fig. 33). State of the art software systems allow a quantitative analysis of the model following results. It can be based for instance on statistical algorithms which are dependent on the time or the frequency. Also very particular evaluations are possible, based on quality criteria related to the given technical problem. The following two subsections deal with two examples for analytical evaluations.

The first approach is defined in the frequency domain. It gives information about aspects of the dynamic performance and the short term model following quality. The second method is one example how model following fidelity can be handled in the time domain. The quality in the long-term range and for instance drift effects can be evaluated.

The experience which has been gained working with both approaches is, that frequency domain and time domain are both necessary to get information about overall fidelity aspects.

6.1.2 Frequency Domain

It is essential for every in-flight simulation, that the host a/c covers the spectrum of the model system dynamics in a given range. Requirements in the frequency domain provide the optimal background to investigate this aspect.

The existing experience in the field of handling qualities investigations can be used. [22] found out that especially for pilot-in-the-loop situations the total system bandwidth and the phase delay are essential. These are the critical parameters for system stability and handling qualities.

Other investigations, e.g. [23], have shown, that added dynamics of about ±2 dB in magnitude and about ±10° in phase at the total system bandwidth frequency are below pilots perceptibility. Based on this result [20] defined a simulation fidelity criterion, which is illustrated in Fig. 30 in principle. The figure shows the above mentioned boundaries applied to the

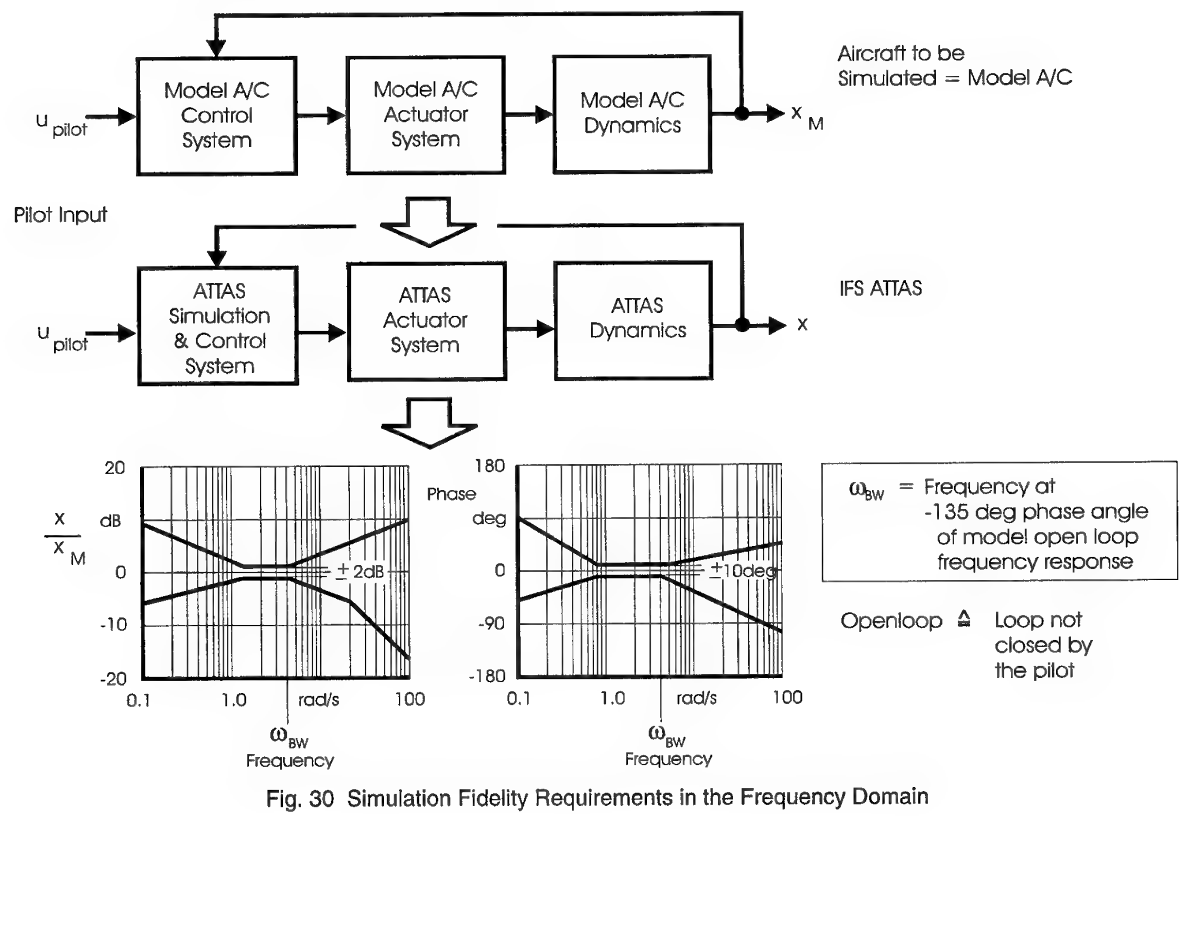

Fig. 30 Simulation Fidelity Requirements in the Frequency Domain

transfer function of simulator response **x** versus the response $\mathbf{x}_m$ of the simulated a/c in the sense of simulation fidelity.

The simulation fidelity transfer function $\mathbf{x/x_m}$ comprises all elements of the model following system given in Fig. 15. The function $\mathbf{x/x_m}$ is nearly identical to the ATTAS actuation system dynamics and the computational time delay caused by the onboard computer system. The reason is based on the fact that the ATTAS-inverse and the ATTAS-dynamics cancel each other up to relatively high bandwidth. Actuation system dynamics and computational time delay are the primary parameters which are responsible for dynamic in-flight simulation fidelity and performance.

Any a/c which has to be simulated contains high order dynamics produced by actuator dynamics and control system delays. The aircraft to be simulated can therefore be described by an ideal a/c dynamics and an equivalent time delay representing high order dynamics. In order to avoid additional time delays on the in-flight simulator the model implemented in the ATTAS onboard computer system contains only the ideal model characteristics with zero time delay because ATTAS' inherent time delays cannot be reduced. As a result the simulation fidelity defined by the allowed phase lag as a function of frequency is given by the difference of high order dynamics of ATTAS and the model. This conclusion can also be understood in a simplified way as the difference of the equivalent time delays (phase delays, respectively). As long as the model phase delay is smaller than the phase delay of ATTAS a phase deviation exists. In the case that both phase delays are equal (zero phase deviation) an optimal simulation is given. For model time delays greater than that of ATTAS, the additional delay has to be taken into account in the model description.

6.1.3 Time Domain

Discussing the fidelity of in-flight simulation in the time domain usually confines to one central aspect. It is the evaluation how well the curves describing model state and host a/c response match. This more quantitative method based on an optical check can be supported by an additional error curve given in Eq. (1):

(1) $$\Delta x(t) = x_H(t) - x_M(t)$$

The result of Eq. (1), the error $\Delta x(t)$, can be used for statistical data evaluation. The standard deviation $s_{\Delta x}$ of the error can be determined.

At the beginning of this section, we described how the engineer usually evaluates the result of a model following control: He tries to find out how well the signal generator input (model a/c) and the output of the system to be controlled (host a/c) match. This way is supported by the following approach which is called "delta rating" ($\overline{\Delta}_R$). It is defined by the ratio:

$$\text{Delta Rating} = \frac{\text{Model Following Error}}{\text{Desired Signal}}$$

The mathematical description is based on the following assumptions and equations:

- The states of model and host are given in a time interval $[t_1, t_2]$.
- The reference states in this time interval can be determined.

It is now essential for the idea of the delta rating, that the deviations from the given reference state of the model a/c are evaluated. These deviations are integrated using the following equation:

(2) $$X(t) = \int_{t_1}^{t_2} \left| x(t) - x_{offset} \right| dt$$

In the case of a flight state, which has to be integrated with equation (2), x_{offset} is the constant reference flight state of the current flight segment. Its value has to be found out in advance.

The model following error (Eq. (1)) is integrated in the following way:

(3) $$\Delta X(t) = \int_{t_1}^{t_2} \left| \Delta x(t) \right| dt$$

With the integrals (2) and (3) a mathematical interpretation of the delta rating can be given:

(4) $$\overline{\Delta}_R = \frac{\Delta X(t)}{X(t)}$$

The simple nature of $\overline{\Delta}_R$ provides a direct impression of the model following quality. Two typical values can be distinguished in an exemplary way:

$\overline{\Delta}_R = 0$: The two curves, which have to be compared, are identical.

$\overline{\Delta}_R = 1$: The plane under the error curve is equal to the plane under the curve of the desired signal. This would be an example of a bad ratio.

Fig. 31 illustrates an example with the help of three sinusoidal functions. The constants are selected as follows:

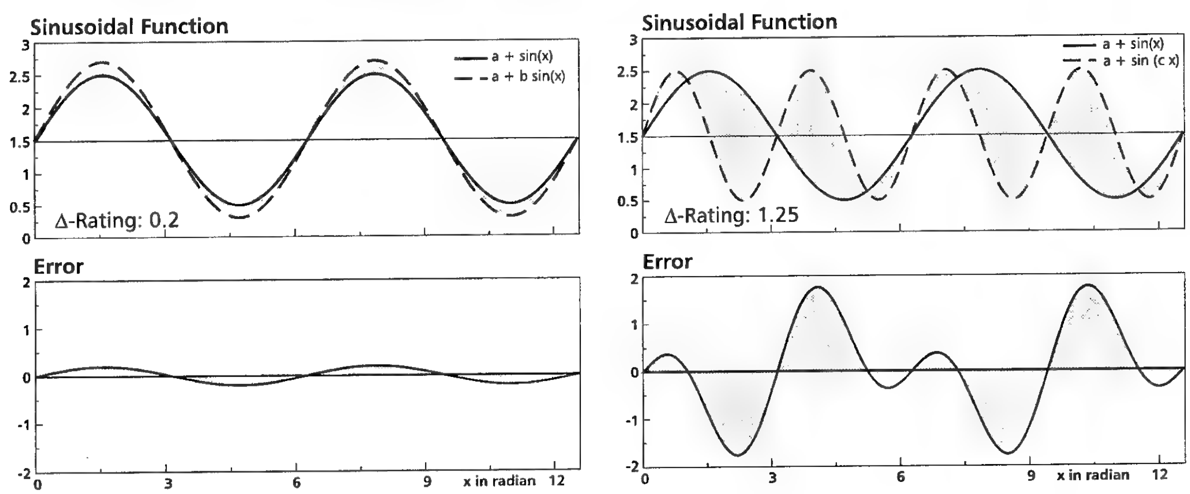

Fig. 31 Examples of Delta Rating Applications

$a = 1.5 = x_{offset}$

$b = 1.2$

$c = 2$

[18] describes this method in greater detail.

6.2 Applications of the Evaluation Methods

6.2.1 In-Flight Simulation of a Spaceplane

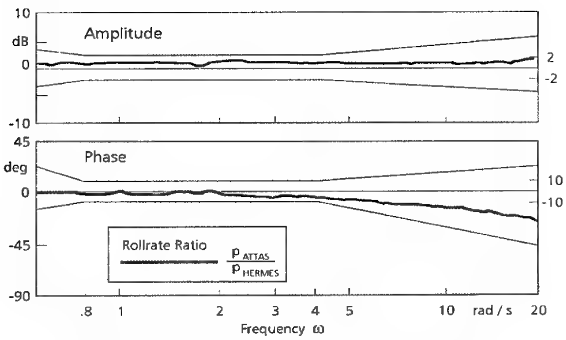

Fig. 32 HERMES Dynamic Simulation Fidelity

Fig. 32 shows the application of the criterion described in section 6.1.2 to the in-flight simulation of the European spaceplane HERMES (the HERMES project was canceled meanwhile). It can be seen that the simulation fidelity requirement is completely fulfilled by the ATTAS in-flight simulation system.

6.2.2 In-Flight Simulation of a Widebody Transport A/C

Fig. 33 shows the pitch angles of model a/c and host, which were recorded during a standard ILS-approach simulated in flight. The simulated a/c was a nonlinear model of a widebody transport a/c (two engines, 115 tons).

The testpilot performed the landing approach as follows:

Flying straight at a level of about 820 m (2690 ft) the pilot captured the localizer of the particular airport. At 100 sec the pilot reached the glidepath of the ILS. He changed the configuration of the model and the host a/c to landing configuration. The landing gear was extended and the simulated a/c as well as ATTAS began the descent. The standard deviation for the error curve in this example is: $s_{\Delta Q} = 0.344°$.

This error is not perceptible by the evaluation pilot. The delta rating can also be applied to the flight-test result given in Fig. 33. The rating for the model following quality for the pitch angle is: $\overline{\Delta}_{R,\Theta} = 0.37$.

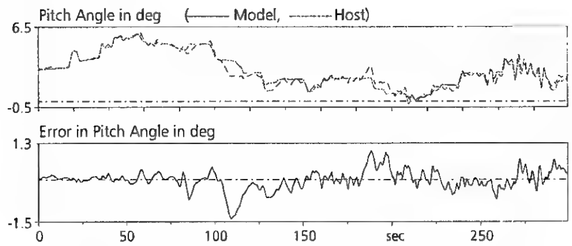

Fig. 33 Pitch Angles during an ILS-approach

It can be seen that the standard deviation as well as the delta rating indicate a good model following for the pitch angle. The Euler angles play a dominating part in the in-flight simulation, because they are controlled directly by the pilot. They are modeled adequately in this case and not only in the longitudinal motion, which is presented here, but also in the lateral motion (see e.g. [18]). During the last five years, numerous flight-test hours with about fifteen experienced test pilots have been performed. They all gave this in-flight simulation only good or excellent ratings.

6.2.3 Effects of Unmodeled Dynamics

A criterion for the acceptance of the simulation by pilots has been derived by [17] for fixed wing aircraft. Here, the frequency responses of measured simulator rates are compared to the commanded model rates. Ideally, the frequency response should have a magnitude relationship of one and a phase angle of zero for a broad frequency range. For practical use, boundaries of so called unnoticeable dynamics were defined, where pilots will not notice simulation deficiencies. Using this criterion also as a quality assessment for the ATTHeS simulation, Fig. 34 compares the frequency responses for measured roll rate to model roll rate for two different cases:

- An identified conventional 6 DOF rigid body model was used to define the flight control system
- An identified extended model with rotor DOF was applied for the flight control system design.

It is clearly seen, that only the ATTHeS frequency response based on the extended model lies within the boundaries. As also good pilot ratings for the simulation where given, it confirms the definition of the boundaries and seems to indicate

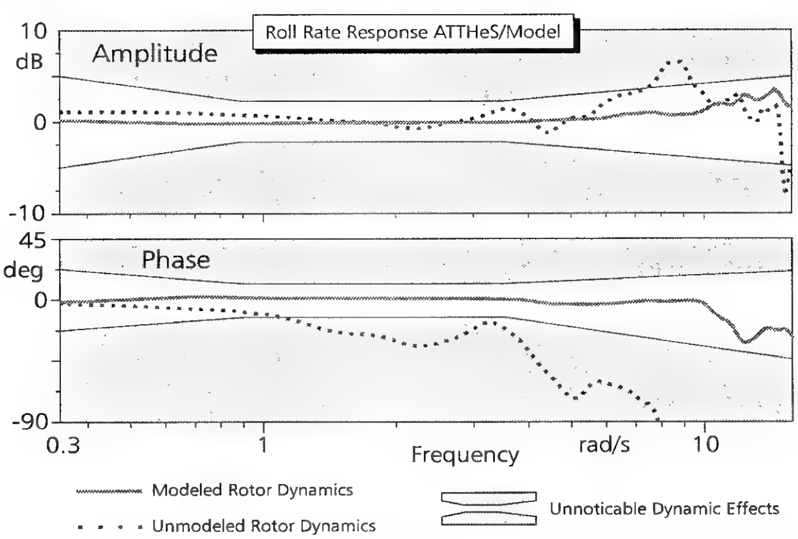

Fig. 34 Effect of Unmodeled Dynamics in the Frequency Domain (ATTHeS)

that they can be used as a more general quality criterion for high bandwidth flight control systems.

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8 ACKNOWLEDGEMENT

This paper is dedicated to the late BO 105 ATTHeS flight test pilot Klaus Sanders and his companion mechanic Hans-Jürgen Zimmer, who decisively contributed to all success of this unique flight test vehicle.

Variable Stability In-Flight Simulator Test Aircraft (VISTA)

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ABSTRACT:

The VISTA is the United States (US) of America's next generation in-flight simulator, replacing the aging NT-33. The VISTA is an F-16D with the Israeli Peace Marble II configuration. The flight control system has been extensively modified to create a state of the art in-flight simulator. The VISTA Phase II Development, Test and Evaluation (DT&E) at the Air Force Flight Test Center (AFFTC) started in July 1994 and was completed in January 1995. The flight test team consisted of personnel from the United States Air Force (USAF), Lockheed Fort Worth Company, and Calspan Corporation. The VISTA flew 62 test sorties for a total of 138 flight test hours at the AFFTC meeting or exceeding all design specifications. The VISTA is owned by Wright Laboratory's (WL) Flight Dynamics Directorate. The Calspan Corporation maintains and operates the VISTA for WL. Using the aerodynamic, mass, inertia, and controller characteristics, and the flight control laws of other aircraft, the VISTA can simulate the aircraft "in-flight" determining the flying qualities and handling characteristics. The USAF and Navy Test Pilot Schools utilize the VISTA in their curriculum. The VISTA is available to support the USAF, other branches of the US Department of Defense, commercial aircraft development, National Aeronautics and Space Administration (NASA) , and foreign military aircraft development programs. This paper presents a brief summary of the development of the VISTA, the hardware and software modifications that were made to create the VISTA, the VISTA Phase II flight test plan and results, and discusses the future direction of in-flight simulation.

DEVELOPMENT OF VISTA :

The high-performance in-flight simulator used in the past by the USAF was the NT-33A. The NT-33A delivered in 1951, is the oldest flying aircraft in the USAF inventory. It was developed into an in-flight simulator in the late 1950's. The NT-33A has simulated nearly every new fighter aircraft that has entered the USAF inventory, plus several aircraft for the Navy, NASA, and allied nations. The NT-33A has also performed research to help develop a Military Specification for flight control and handling qualities. As the in-flight simulation demands of new aircraft have become more complex, the NT-33A no longer represented modern high-performance aircraft. The NT-33A is also no longer logistically supportable based on cost. Seeing the end of the useful life of the NT-33A a contract was awarded to the Calspan Corporation in 1982 to define the requirements for a replacement.

The F-16D was selected as the best replacement for the NT-33A meeting the following requirements: 1) Two-seat fighter-type aircraft with the front cockpit to be the evaluation cockpit with variable feel controls with programmable displays and the rear cockpit to be the pilot-in -command (safety pilot); 2) The Variable Stability System (VSS) must be capable of all-attitude model-following and response feedback simulations; 3) The in-flight simulator must be able to control the six degree-of -freedom forces and moments to satisfy mission and simulation fidelity requirements,and; 4) It must be relatively inexpensive to operate.

The F-16D was modified during production at Lockheed Fort Worth, TX to produce the VISTA aircraft. The VISTA modification contract was awarded to Lockheed

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in August 1988. All the VISTA hardware and software modifications were incorporated under this contract. The VISTA development approach was dictated by funding, with the baseline effort consisting of a five degree-of-freedom capability, hydraulic systems upgrades, a response feedback variable stability system, and extensive cockpit modifications. Planned upgrades will add a model-following capability, extend the simulation envelope to supersonic, increase the bandwidth of the integrated servoactuators, add tactile cueing to the aft seat controllers, provide a variable feel sidestick and rudder pedals, and add thrust vectoring capability.

The baseline VISTA development approach included the DT&E flight test effort which was completed in two phases. Phase I of the DT&E flight test effort was completed at Lockheed Fort Worth in April 1992. The Phase I DT&E demonstrated that VISTA could fly/operate like a F-16 and consisted of five sorties and 5 flight test hours. The VSS and safety trips were not tested. Funding constraints prevented the USAF from starting the Phase II DT&E effort immediately after the Phase I effort was completed. The VISTA was put in flyable storage until it was modified and used as the test bed for the Multi-Axis Thrust-Vectoring (MATV) engine test program at EAFB during the July 93 through March 94 time period. The airplane was modified back to the original VISTA configuration after the MATV flight test program was completed. The VISTA Phase II DT&E flight test program flew 62 sorties, 138 flight test hours, started July 94, and was completed January 95.

TEST ITEM DESCRIPTION:

The production VISTA F-16 (Type Version IV) includes the large dorsal fairing (extending aft from the canopy to the vertical tail) and heavy weight landing gear. This Block 30 configuration is based on the Israeli Air Force Peace Marble II (PMII), Type Version 4K, F-16D airframe. Unnecessary systems and hardware such as the 20mm gun system, ammo drum, radar warning system, chaff/flare dispenser, nuclear weapon capability, AMRAAM missile capability, and HUD expanded envelope gun sight capability were deleted from the VISTA design. The aircraft is powered by a General Electric F110-GE-100 engine, and has an APG-68 radar, and a digital flight control system. The hydraulic system flowrate was increased, the flaperon and horizontal tail actuators modified for increased rate, and modifications to the electrical and avionic systems were made to the VISTA. The VISTA was completed by adding the VSS equipment and making the cockpit changes required to support the VSS operation. The general arrangement of the airframe and the VSS equipment is shown in Figure 1.

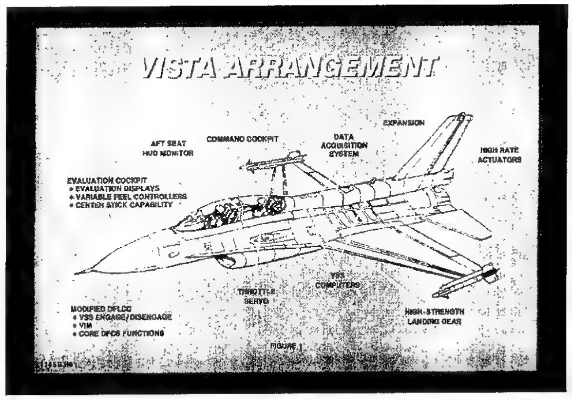


FIGURE 1

The VISTA cockpits are extensively modified from the production F-16 cockpit baseline configuration. Major changes include the addition of several controls and displays to both cockpits and the relocations of primary controls and displays to the aft cockpit. The front cockpit or evaluation cockpit has a movable variable feel centerstick controller in addition to the F-16 sidestick controller. Both sticks, the rudder pedals and the throttle interface with the VSS during a simulation. The throttle in the front cockpit is not mechanically connected to the throttle in the rear cockpit. The aft or safety cockpit has all primary controls required for single pilot operations as well as secondary controls. A HUD monitor, capable of repeating the HUD information, has been installed on the safety pilot's glareshield.

VARIABLE STABILITY SYSTEM (VSS)

The key to the modification of the VISTA is the installation of the VSS that interfaces with the Digital Flight Control System (DFLCS) allowing the aircraft to fly with a variety of control laws. The VSS utilizes the response feedback method for simulation. The VSS provides limited five degree of freedom simulation capability. The system commands symmetric and asymmetric horizontal tail movement, symmetric and asymmetric flaperon movement, rudder, and throttle control. The VSS does not control the leading edge flaps and speedbrakes. Future expansion for explicit model following capability is an option. Major airborne components of the VSS include three Rolm Hawk 32 digital computers with an input/output expansion chassis, a microcomputer, sensors and sensor signal conditioners, circuitry interface chassis, and cockpit controls and displays.

The three Rolm Hawk-32 digital computers control the all-attitude response feedback simulation. The computers have the capacity to accommodate and execute software for feel system characteristics, command feedforward/response feedback mechanization, simulation/configuration management, graphic functions, VSS operational envelope limiting and warning and safety monitoring. A Titan computer performs the function of controlling the variable feel

system on the center stick. The VSS is a single-strand, fail safe system, and commands the quad redundant F-16 control activation system. Figure 2 shows how the VSS interfaces with the DFLCS.

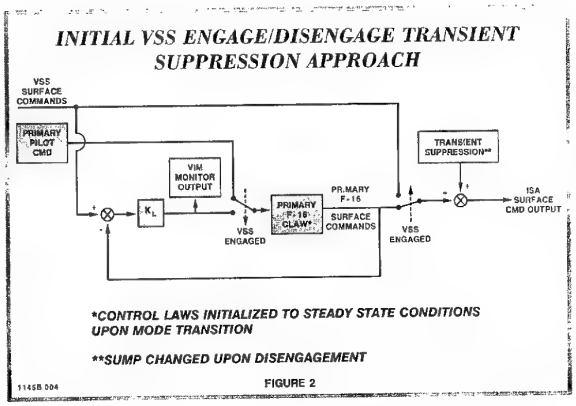


FIGURE 2

The rear cockpit of VISTA is always a F-16 using a normal F-16 side stick controller and production flight control laws. The front cockpit functions in one of three basic modes of flight control; VSS mode, F-16 convenience mode, and F-16 emergency mode. VSS can only be run from the front cockpit. Only one cockpit is active at a time. The VSS mode is used during actual simulation work. The F-16 emergency mode is designed to allow the front cockpit pilot to fly the aircraft using the side stick and normal F-16 control laws. Its purpose is to allow the front seat pilot to recover the aircraft should the rear cockpit safety pilot become incapacitated. The F-16 convenience mode is very similar to the emergency mode in that it also allows the front seat pilot to fly the aircraft while the rear cockpit pilot attends to other duties such as modifying the simulation gains. With either the emergency or F-16 convenience modes selected, the sidestick and rudder pedal controller will interface with the DFLCS and the aircraft will operate with normal F-16 control laws. The difference between the two modes is that in the convenience mode all manual safety trips which revert control to the rear cockpit are still available, and the safety pilot can maintain throttle control if desired.

The flight envelope cleared for the VISTA is shown in Figure 3. The standard F-16 flight envelope was reduced for the F-16 host aircraft for initial operations to reduce the required amount of analysis and testing. The variable stability flight envelope is further reduced to subsonic operation with the option of expanding the envelope in the future. The external loadings cleared for VISTA are shown in Figure 4. For the F-16 host aircraft operations, structural loads have been cleared to 100% of the allowable design limit load for external loadings. For VSS operations, structural loads have been cleared by analysis to 80% of the allowable design limit load resulting in reduced g envelopes. Special monitoring functions within the DFLCS have been designed to disengage the VSS when commands from the VSS to the DFLCS result in loads greater than 80% of allowable design limit load.

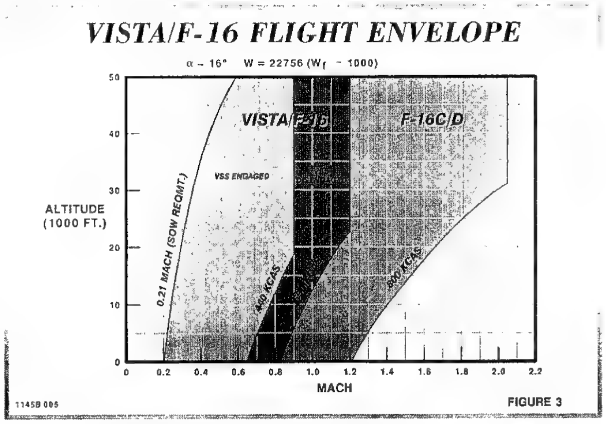


FIGURE 3

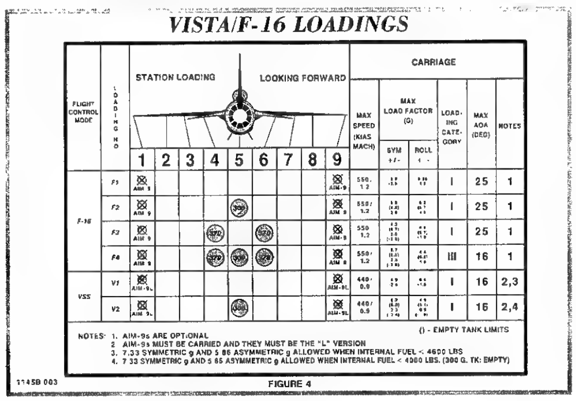


FIGURE 4

TEST OBJECTIVES/SCOPE

The general test objectives for the VISTA Phase II flight test program were:

1. To verify the safety and integrity of the aircraft with the VSS engaged.

2. To expand the VSS envelope by determining gain and maneuver limits.

3. To demonstrate the aircraft's simulation capabilities for research and student training missions.

The specific test objectives for the VISTA Phase II flight test program were:

1. To evaluate the transients during VSS engagements, disengagements, and mode changes in 1 g and maneuvering flight.

2. To verify and develop the functions of the VISTA Integrity Management (VIM) and VSS safety trip systems.

3. To develop and determine the effectiveness and utility of using aeroservoelastic (ASE) detection software to augment the other VSS safety trips.

4. To determine what limits exist on the VSS feedback gains.

5. To qualitatively evaluate the simulation capabilities over a broad range of maneuvers and flight conditions.

6. To determine the effectiveness of the direct lift flaps to support direct lift and pitch pointing maneuvers.

7. To determine the thrust dynamics of the F110-GE-100 engine.

8. To determine basic airframe stability and control parameters to provide a baseline for future simulation developments.

9. To develop and evaluate the safety pilot's ability to safely assume control and recover the aircraft during VSS approach and landing tasks.

10. To evaluate compliance with the Statement of Work requirements that the aircraft be able to simulate selected rigid-body, modal parameters within given ranges.

11. To develop and evaluate the aircraft's ability to simulate specific airplane configurations for research type programs using the X-29 as a model.

12. To obtain user evaluations through demonstration flights to potential VISTA users.

FLIGHT TEST RESULTS

The VISTA Phase II flight test plan shown in Figure 5 delineates the order in which the test blocks were completed. The safety/safety trip related flight test points were flown first. The gain build up testing followed determining the gain limits. Once the safety trips and gain limits were determined the in-flight simulation capabilities test points for VISTA were flown followed by the demonstration test points.

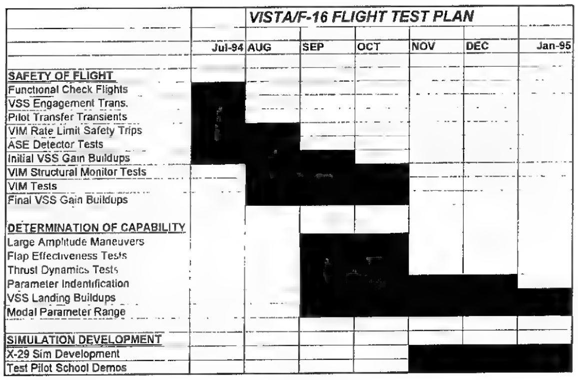


FIGURE 5

ENGAGEMENT AND PILOT TRANSFER TRANSIENTS

The test program was initiated by performing functional check flights. The VSS engagement transients and pilot transfer transients were tested next to determine the response characteristics of the aircraft after VSS engagements and pilot transfers at various initial conditions. Testing was conducted at medium altitude, beginning at medium airspeeds and progressing to low then high airspeeds and dynamic flight maneuvers. The pilot transfer transients were evaluated by engaging the VSS, getting to the desired initial condition, and having one pilot manually transfer control of the VISTA to the other pilot . These tests also evaluated the safety pilot control force safety trips. There were no significant transients experienced during these tests.

VIM AND ASE TESTING

The VISTA Integrity Manager (VIM) rate limit safety trip testing was performed by sending automatic test inputs to drive individual flight control surfaces below rate trip levels to verify that rate limits do not occur and to drive surfaces at their respective rate limits to cause a safety trip. After the VIM was verified some work was performed on the Aeroservoelasticity (ASE) detectors. These detectors were considered a backup safety trip and were not required to perform flight test. The ASE detector development was ongoing during the remainder of the flight test program.

The VIM structural monitor tests and the remaining VIM monitor tests developed and verified the automatic safety features of the DFLCS. These tests completed the safety trip evaluations. These tests were performed in a buildup manner, beginning with medium/low airspeeds and benign maneuvers, then progressing to higher airspeeds and more aggressive maneuvers. The VIM structural monitor safety trips generally tripped as designed, but there were some cases where the safety trip design was more conservative than the prediction. Both manual and automatic inputs were used to verify the VIM safety trips. Table 1 list some of the VSS VIM trips . An example of the structural limit boundary is given in Figure 6 for the asymmetric horizontal tail. The structural limits affect simulation if negative flap deflection is required such as when simulating an n/α lower than the F-16's.

Table 1

VIM TRIPS AFFECTING VSS OPERATING ENVELOPE

	Limits	*Persistence*
$-n_z$	7.33, -2.4 g	none
n_y	± 5 g	none
α	16 , -10 deg	none
β	±10. deg	none
M, V	440 kts and M = .9 (see Figure 1)	none
pitch mon.	8. -5. g	none
roll mon	±300. deg/sec	none
yaw mon	±30. deg	none
$\dot{\delta}_{H_{R_c}}$	±70. deg/sec	115 ms
$\dot{\delta}_{H_{L_c}}$	±70. deg/sec	115 ms
$\dot{\delta}_{F_{R_c}}$	±70. deg/sec	500 ms
$\dot{\delta}_{F_{L_c}}$	±70. deg/sec	500 ms
$\dot{\delta}_{R_c}$	±100. deg/sec	250 ms
δ_{H_c}	no trip, deg.	–
$\delta_{H_{A_c}}$	N42, N43 deg	7 VSS frames
δ_{F_c}	N44, N45 deg.	7 VSS frames
$\delta_{F_{A_c}}$	N46, N47 deg	7 VSS frames
δ_{R_c}	N48, N49 deg.	7 VSS frames

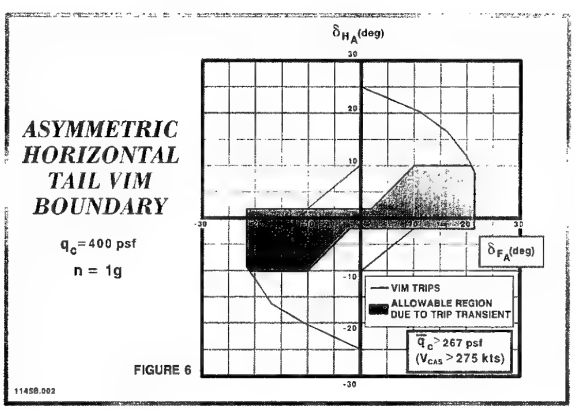


FIGURE 6

GAIN BUILD-UP TESTING

The initial VSS gain build up testing was performed to clear VSS configurations that were used in the structural monitor and VIM tests. The final gain buildups cleared the remainder of the VISTA envelope and these test points were completed after the VIM tests were completed.

The gain build up testing was performed using a single gain procedure, and double gain procedure. The gains were increased until the modal parameter goals in the statement of work were reached or when the aircraft response no longer fit the desired lower order equivalent system model response due to ASE interactions. The single gain procedure evaluated primary gains, which are defined as most often used in in-flight simulations. An example of a primary gain is elevator per angle of attack rate (E/αDOT). The double gain procedure tested a new primary gain in conjunction with a previously tested gain. The new primary gain was increased to its gain limit while keeping the previously test gain at a constant value. This would be done three times by increasing the previously tested gain until the gain limit was reached (example: 40%, 80%, and 100%). In the gain build-up tests the gain was run open loop and 2-25 Hz white noise was injected into the flight control system exciting the desired response. Using the real time frequency analysis system MASSCOMP (Nyquist plot & frequency spectrum plot), a gain margin and value for instability was predicted. The starting point for the close loop testing was then taken as 50% of the predicted instability values. Accelerometers on the wing tips, horizontal tail, and vertical tail allowed the structural mode damping to be monitored.

LARGE AMPLITUDE MANEUVERS, FLAP EFFECTIVENESS, THRUST DYNAMIC TESTING, AND PARAMETER IDENTIFICATION TESTING

The large amplitude maneuvers were designed to allow the pilots to fly VISTA aggressively at all attitudes and at a variety of conditions to determine if the safety trips were too conservative. The design of the safety trips was considered acceptable by the pilots. This subjective evaluation was made by all pilots. The flap effectiveness testing recorded data at trimmed flight conditions with various flap deflections. The thrust dynamic testing evaluated throttle servo response and aircraft response to throttle commands. Parameter identification tests provided the data necessary to derive the basic airframe longitudinal and lateral directional equation parameters.

MODAL PARAMETER TESTING

The VISTA modal parameter design goals follow:

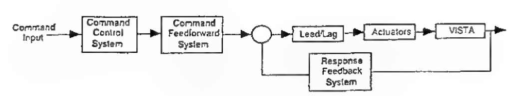
Short Period: Frequency 0.0 to 15 radians/sec
Damping Ratio -0.1 to 1.1

Dutch Roll: Frequency 0.0 to 8.0 radians/sec
Damping Ratio -0.1 to 1.0

Roll/Spiral: Frequency 0.0 to 5.0 radians/sec
Damping Ratio -0.1 to 1.0

ANALYSIS APPROACH

Time response analysis was used to determine the range of dynamic characteristics that the VISTA can simulate. For each dynamic mode, a specific VISTA response was matched to an equivalent lower order model response to determine the modal parameters. The VSS control law configuration used for modal parameter flight tests is shown in Figure 7.

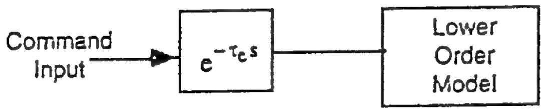


VISTA VSS CONTROL CONFIGURATION

FIGURE 7

For modal parameter tests, the Command Control system was represented by a pure gain. The command feedforward system distributes the command control to the various VISTA control surfaces. The Response Feedback System provides feedback from VISTA sensors to the control surfaces. The actuator lead/lag compensation provided the capability to use high sensor feedback gains necessary to achieve the goal for the modal parameter range with the existing low bandwidth actuators. Specific test inputs (step and doublet) were used to excite the VISTA for various feedback configurations. To determine the modal parameters, a

specific VISTA response was matched to the response of an Equivalent Lower Order Model (LOM). The equivalent LOM is shown in Figure 8.



EQUIVALENT LOWER ORDER MODEL

FIGURE 8

The LOM parameters are determined by matching the LOM response computed for the same command input used during flight tests, to the VISTA response. The LOM is either first order or second order depending on the VISTA response being matched. The LOM parameters are adjusted to minimize the error between the model and VISTA responses. The criterion used for optimizing the equivalent model parameters is defined as

$$\text{(1)} \qquad \text{Error} = \frac{1}{T_2 - T_1} \int_{T_1}^{T_2} |X_{model} - X_{VISTA}|\, dt$$

where X_{model} is the LOM response, X_{VISTA} is the VISTA flight response, and T_1 and T_2 are the start and the final times of the flight test, respectively. A particular VSS gain set or configuration is accepted if the lower order model parameter set satisfies the following requirement:

$$\text{(2)} \qquad \text{Minimum Error} < 0.15 \frac{1}{T_2 - T_1} \int_{T_1}^{T_2} |X_{model}|\, dt$$

The match of the LOM time response to the VISTA response was accomplished through nonlinear optimization. The error criterion of Eq (1) was minimized using the technique of Fletcher and Powell.

MODAL PARAMETER RESULTS

The Short Period mode was extracted by fitting a second order model to the VISTA angle of attack response to a horizontal tail test input. Two types of second order model were used. For the complex short period mode, the second order model form used was:

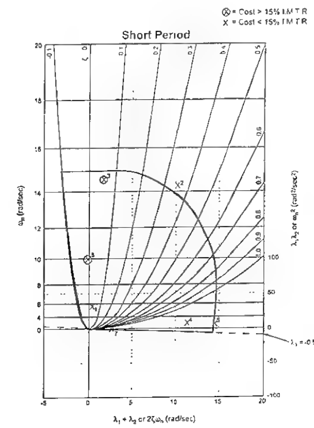
$$\text{(3)} \qquad \frac{Output}{Input} = \frac{Ke^{-\tau_e s}}{s^2 + 2\zeta\omega s + \omega^2}$$

For the case when two Short Period was represented by two real roots, the second order model form used was:

$$\text{(4)} \qquad \frac{Output}{Input} = \frac{Ke^{-\tau_e s}}{(s+\lambda_1)(s+\lambda_2)}$$

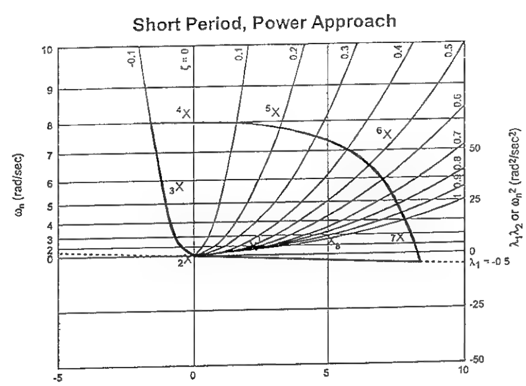
The model response was matched to the flight response by adjusting the parameters K, ζ, and ω to satisfy the error criterion. The equivalent time delay, τ_e, was held fixed at 100 msec during the matching process. This time delay value was based on the best available estimate of equivalent time delay due to the VISTA actuator, computations and signal conditioning and confirmed through flight data analysis.

The results for the Short Period modal parameter optimization runs cruise condition are shown in Figure 9 and the runs for power approach condition are shown in Figure 10.



Short Period Modal Analysis Results

FIGURE 9



SHORT PERIOD MODAL ANALYSIS RESULTS

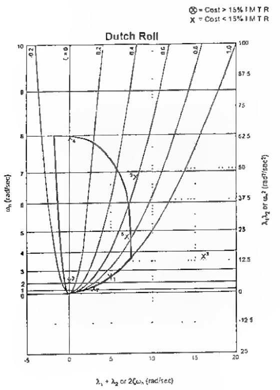
FIGURE 10

The dark lines in the figure represent the goal for the Short Period modal boundary. The points that are circled represent the modal parameter optimization runs that slightly exceed the cost criterion but are acceptable based on the observed fit. The goal for the modal parameter limits are reached with the specified feedback gains and any point within the boundary can be obtained. The response feedback gains used were E/α and

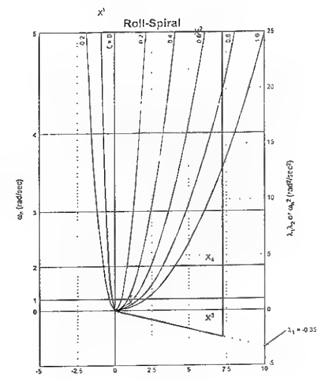
E/αDOT, representing the feedback from the complementary filter angle of attack and angle of attack rate, respectively, to the horizontal tail.

The Dutch Roll mode was extracted by fitting a second order model to the VISTA sideslip response to a rudder test input. As with the Short Period case, two types of second order model were used: the first type to extract the damping and frequency and the second type to extract two real roots. Figure 11 presents the results for the Dutch Roll analysis for cruise condition and Figure 12 present the power approach condition results.

to the short term VISTA roll rate response, where λ_1 is the estimated roll mode and λ_2 is the spiral mode to be estimated. For the case where the roll and spiral modes were not separated widely, the second order model of equation (4) with two real roots was used to fit the VISTA bank angel response. For the case where the roll and spiral modes combined to form a complex pair, a second order model with damping and frequency was used to fit the VISTA bank angle response. Figure 13 presents the results of the roll spiral modal parameter optimization runs for cruise condition and Figure 14 presents the results for the power approach condition.



Dutch Roll Modal Analysis Results
FIGURE 11



26.58
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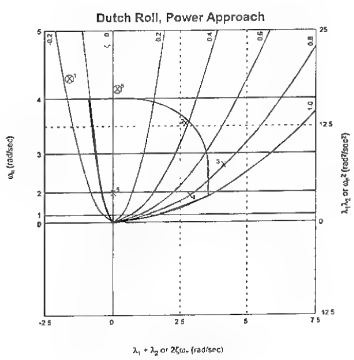
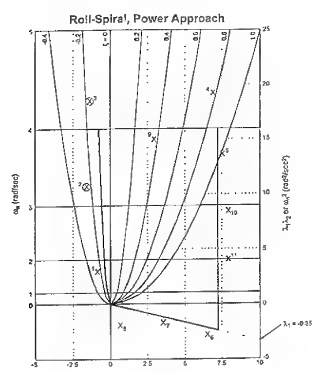
Roll-Spiral Modal Analysis Results
FIGURE 13



DUTCH ROLL MODAL ANALYSIS RESULTS
FIGURE 12



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ROLL SPIRAL MODAL ANALYSIS RESULTS
FIGURE 14

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The dark lines in the figure representing the goal for the Dutch Roll. The response feedback gains used were R/β and R/βDOT, the feedback from the complementary filter sideslip and sideslip rate, respectively to the rudder. The actuator time delay was set at 100msec for each run.

The Roll Spiral modes were extracted using three different types of lower order models. For the case where the roll and spiral time constants were far apart, the roll mode time constant was extracted by fitting a first order model,

$$(5) \qquad \frac{Output}{Input} = \frac{Ke^{-\tau s}}{(s+\lambda_1)}$$

The response feedback gains used were A/P and A/Φ representing the feedback from the VISTA roll rate and bank angle, respectively, to the flaperon. The time delay for each run was 100 msec.

LANDING BUILD-UP RESULTS

The purpose of the landing build-up tests was to demonstrate that the safety pilot could recover VISTA from an upset during a landing approach. The testing started at 10,000 feet AGL and worked down to lower altitudes and finally touchdown. All four pilots practiced recoveries at 10,000 feet AGL. The high altitude tests did not provide evidence preventing

repetition of the tests at lower altitudes. Simulated approaches were then flown in the landing pattern with known and unknown upsets input at 500, 250, and 200 feet AGL. The six upsets used were pitch up, pitch down, roll (left and right), yaw (left and right), slowing to high AOA, and throttle back. The upsets were input by the evaluation pilot when the safety pilot knew what the upset was going to be. The evaluation pilot then input upsets when the safety pilot did not know which upset he would have to recover from. The altitude lost after an upset varied with the different pilots. The pitch down upset caused the largest altitude loss as expected, about 80 feet. The pilots were not pressed by a high sense of urgency to recover at these altitudes.

The next step was to perform approaches with known and unknown upsets to 50 feet AGL. This allowed the safety pilot to sense visual cues such as sink rate, runway alignment, and aircraft attitude. The safety pilots had an increased sense of urgency to recover the aircraft quickly. The standard recovery technique was to level the wings, raise the nose, apply full throttle, and close the speed brakes. This recovery technique worked well for all six upsets.

Approaches were then made below 50 feet AGL with a 75 msec time delay added in the roll and pitch commands. None of the six hard over upsets were input by the evaluation pilot below 50 feet AGL. Small nondivergent Pilot Induced Oscillations (PIO) were induced when flying the configuration with added time delay. Several safety trips were encountered at 10 feet AGL and the safety pilots recovered easily without any problems.

The actual landings were performed with the VSS programmed for Cooper-Harper Level 1 flying qualities and Level 2 flying qualities. The Levels were determined up and away. Inserting a time lag in the pitch and roll axis allowed Level 2 flying qualities to be obtained. All landings were touch and goes with the Level 1 VSS configurations and were uneventful. The Level 2 handling qualities landings were essentially uneventful so a turbulence generator was added during the approach, again recoveries were made with no significant degradation. No Level 3 handling qualities approaches were flown.

DEMONSTRATION AND X-29 SIMULATION TESTING

The Test Pilot School (TPS) test flights demonstrated that VISTA could satisfy the curriculum of both the Air Force and Navy TPS's. Pilots from both TPS's flew VISTA and were satisfied that their respective in-flight simulation curriculums can be completed with VISTA. The X-29 simulation development evaluated the ability of VISTA to accomplish specific airplane simulations for research-type programs. Specific points in the sky were selected and verified that VISTA could simulate the X-29 at those test points.

FUTURE DIRECTION OF USAF IN-FLIGHT SIMULATION

The end of the Cold War generated a new political environment which reshaped the USAF of the 1990's. These new realities are forcing the USAF to increase efficiency with fewer people and lower funding. The remaining resources must be reorganized and prioritized to allow greatest benefit for the dollar to be realized. The Air Force can no longer afford to develop, own, and operate facilities that duplicate those already in existence, regardless of whether they are government or civilian owned. Any duplication must be justifiable based on military need. If a service can be obtained elsewhere in a timely manner and satisfies the need, then it must be obtained from that source. USAF test facilities are being reviewed to eliminate duplication and in some cases eliminate a test capability. In-flight simulators were identified as a unique military facility with no comparable civilian capability; however, their survival is not assured. In today's environment, the survival of in-flight simulation depends on keeping these aircraft flying while minimizing the fixed costs. The realities of the 1990s defense budgets forced the in-flight simulation to branch out from the traditional missions and pursue non-traditional missions and non-traditional customers, presenting exciting new challenges and possibilities.

TRADITIONAL IN-FLIGHT SIMULATOR MISSIONS

The traditional mission of the in-flight simulator can be categorized into the following four areas; pre-first flight evaluation of new/modified aircraft, research and development, specialized training, and flying laboratory.

The pre-first flight evaluation of a new or modified aircraft is what in-flight simulators are most noted for, but this type of simulation is actually a small portion of the total in-flight simulator work because the U.S. military does not develop new aircraft often. USAF programs that utilized in-flight simulations include bombers such as the B-1 and B-2, fighters such as the F-15, F-16, F-18, JAS-39 Gripen, Lavi, YF-22, and YF-23. research aircraft such as the X-15, AFTI/F-16, and X-29, the Space Shuttle and commercial developments.

Research and development is the mission for which in-flight simulators first were developed and operated. They are ideally suited for flying qualities research and many other R&D efforts because the flight characteristics can be easily changed and the effects of new controls, controllers, or control mechanizations can

be demonstrated to test pilots and flight test engineers. This is especially true for evaluating new flight control concepts, developing flying/handling qualities specifications, and testing displays and human factors concerns.

Specialized training missions primarily support training at the Air Force and the Navy test pilot schools. The specialized training missions account for about half of the in-flight simulator flying hours, which helps to decrease the cost to all in-flight simulation customers. Examples of the specialized training mission include the NT-33 which was used for nearly twenty years to demonstrate a wide variety of flying qualities and HUD formats. In a one and a half hour flight, about thirty different combinations of aircraft dynamics, stick dynamics, control system feedbacks, time delays, and HUD formats were demonstrated. The VISTA replaced the NT-33A in this role, with a new flight syllabus oriented toward the VISTA's capabilities. The NC-131 is used to train pilots and engineers to test avionics. Test techniques are taught in a comfortable but real airborne environment. In this role, the NC-131 is configured with radar, FLIR, and E/O sensors, and INS, GPS, and LORAN navigation systems. Many internal parameters of these avionics systems can be accessed through a special computer and data bus.

In-flight simulators make excellent flying laboratories. The MATV program is an example of how VISTA has been successfully used as a flying laboratory. The aircraft are already highly instrumented, and the procedures for designing and approving the installation of new or special test equipment are well established.

NON-TRADITIONAL IN-FLIGHT SIMULATOR MISSIONS

The non-traditional mission for in-flight simulators is to serve as technology demonstrators and test beds. Technology demonstration programs are not new for in-flight simulators, but they were not used significantly in the past. In the past, special test aircraft were dedicated to demonstrating new technologies. Examples included the AFTI-16 and AFTI-111 programs. In-flight simulators were seldom used for these applications because it required the aircraft to be dedicated to that effort for extended periods denying other programs access to their aircraft. Also they seldom needed simulation capability to accomplish their mission. The Air Force's in-flight simulators will certainly compete in the future to perform this function. It is anticipated that such programs, if structured carefully, can be performed without causing undue loss of ability to support other needs.

Another non-traditional mission for the in-flight simulator is to serve as a test bed for developing F-16 flight control system upgrades. With production F-16s having a digital flight control system, new software is simple to install in the field; however, developing, verifying, and flight testing the new code is a lengthy process. Proposed software changes normally must undergo an extensive verification and validation (V&V) process before being tested in an aircraft to verify that the original problem has been corrected. Using the VISTA, proposed software changes that have not been V&V'd can be installed in the variable stability system and flight tested to verify proper operation. If the new software change fixes the original problem, it can then be V&V'd for fleet-wide use. It would also be possible to install an actual F-16 digital flight control computer in VISTA in addition to the variable stability computers for testing new code. This use can significantly decrease the cost of developing new software for operational F-16s.

This concept can be extended to other existing aircraft and aircraft under development by using the VSS to replicate the bare airframe characteristics of those aircraft.

The technology demonstrator and test bed capability of the VISTA will be augmented by the installation of a permanent thrust vectoring capability. This upgrade will make VISTA the Air Force's only thrust vectoring/high angle of attack research aircraft, in addition to giving it a greatly increased simulation capability. This effort is currently funded and the work breakdown is being adjusted to match the funds available over the next several years. With a shrinking number of test assets and customers, the in-flight simulators will be used as technology demonstrators and test beds provided other critical programs can still be supported.

NON-TRADITIONAL IN-FLIGHT SIMULATOR CUSTOMERS

With fewer projects being sponsored by traditional customers, new customers are being sought. In addition, some regulations/instructions that are no longer consistent with the new economic environment are being rewritten making in-flight simulation available to almost anyone that can pay the program cost.

In the past, virtually all in-flight simulations were performed by either the Air Force, Navy, or NASA. The new, more stringent economic situation is forcing program management to look beyond the traditional customer base for new project sponsors. Newer customers include U.S. industry, foreign government programs performed through Foreign Military Sales, and foreign industry. American commercial programs have been performed since the mid-1980s, but new regulations now make it relatively easy to allow industry to use unique military facilities. Foreign military programs were supported since the early 1980s. Supporting foreign commercial programs is relatively new. A recent TIFS simulation program was the first foreign commercial development ever supported by the Air Force (with no regulations in place to provide guidance for this situation, lengthy high-level coordination was required

until permission to perform the program finally was obtained). Efforts to find new sponsors will be expanded in the future, as well as continuing to make the aircraft available to traditional customers.

OPERATION CONCEPT FOR IN-FLIGHT SIMULATORS

The new economic environment is impacting the operation of in-flight simulators, but not as badly as many other R&D facilities. Up until the mid-1970s, the TIFS and NT-33A were completely funded by Wright Laboratory. Most projects flown were to support in-house needs, but based on priority, projects for other government agencies also were flown. This changed about 1975 when the laboratory considered terminating the program. The program was saved, but made self-supporting. The lab would provide some seed funds for a very basic level of maintenance, proficiency, and system upgrades. The program management would have to identify all costs for performing specific projects and the sponsor would have to pay those costs in order to see their project flown. By the late 1980s, this support grew to about $200,000 per year from the laboratory with an additional $500,000 per year or more from headquarters for depot-level maintenance.

Over the last three years the above mentioned support funds were reduced and ultimately terminated. The new environment's impact in the in-flight simulators is not procedural, but monetary. With support funds gone, all costs now must be paid by sponsors as part of using the aircraft. With the TIFS and NT-33A each flying about 200 hours per year, the impact is a cost increase of over $1500 per flight hour.

The new environment extends also to spare parts obtained from Air Force depots. In the past, the depots were funded to provide spares and overhauled components for whoever needed them. About three quarters of the cost was absorbed by the depots, making many of the needed components "free" to the users. This changed as well; all parts now must be paid for by the user and the cost passed on to the project sponsor.

The operating concept for Air Force in-flight simulators remains unchanged. The four key elements remain government ownership, contractor operation, base at contractor facility, and use of a task ordering contract. This concept evolved over thirty-five years of operating in-flight simulators. It allows the Air Force to take advantage of the positive elements of government and industry working together, while eliminating the negative aspects of each. A detailed discussion of this concept has been documented elsewhere[1]. Prior to the VISTA becoming operational, this operating concept was reviewed and determined to still be the most viable means for operating in-flight simulators.

FUTURE IN-FLIGHT SIMULATION PROGRAMS

Despite the decrease in R&D budgets, the in-flight simulation program remains viable. These aircraft proved they provide a unique capability, and serve an essential need not duplicated anywhere within the government or civilian sectors.

The TIFS/NC-131H is committed to three programs in the near future. These are to support NASA's effort in developing technologies for the High Speed Civil Transport, to continue to perform research in the area of large aircraft flying qualities for Wright Laboratory and Douglas Aircraft, and to simulate the Indonesian Nusantara N250 commuter aircraft.

The VISTA also has several commitments. Following installation of a permanent thrust vectoring capability, VISTA will be the Air Force's high angle of attack/post stall maneuvering research aircraft. It will also support development of the F-22 and Indian Light Combat Aircraft. The Joint Advanced Strike Technology (JAST) program plans to use VISTA to aid in developing technologies for future strike aircraft, but exact utilization has not been determined. The Air Force and Navy test pilot schools also plan to continue using VISTA. The aircraft made its first deployment to the schools in March and April 1995.

CONCLUSION

The Phase II VISTA flight testing at the AFFTC showed that VISTA can support the high performance in-flight simulation of the future for the USAF. Once the VISTA upgrade program is completed VISTA will have a thrust vectoring capability. Thrust vectoring will allow VISTA to support high AOA technology demonstrations and in-flight simulations. The VISTA is available for new missions as a technology demonstrator and as a test bed. New VISTA customers are also being pursued including foreign commercial customers.

1. Markman, Steven R., USAF In-Flight Simulation: A Cost-effective Operating Approach, AIAA Flight Simulation Technologies Conference, Monterey CA,

EXPERIENCES ACQUISES LORS DE LA MISE EN OEUVRE DES PROTOCOLES SID AVEC DES SIMULATIONS DEJA EXISTANTES.

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SOMMAIRE

Le besoin de coupler des simulateurs ou des simulations croit chaque jour et la diversité de ces simulations est très grande. Des expériences passées ont montré qu'il est presque impossible d'interconnecter des simulations déjà existantes s'il faut pour cela utiliser des méthodes et des structures communes imposées à chaques simulations. L'approche des Simulations Interactives Distribuées (SID) permet de coupler des simulations hétérogènes sans avoir à les modifier de manière importante. De plus les simulateurs déjà existants ont certaines particularités quand on les compare aux simulateurs récents. Ils sont souvent limités en mémoire, puissance de calcul et ont rarement des moyens de couplage à des réseaux de communications.

Ce papier décrit les méthodes et les techniques utilisées pour développer des bibliothèques logicielles mettant en oeuvre les fonctions d'interopérabilité des SID conformément à la norme IEEE 1278. Les exigences principales pour ces bibliothèques étaient : portabilité, masquage pour l'utilisateur des détails du protocole, et flexibilité pour pouvoir s'adapter au large éventail des simulations utilisées dans le groupe THOMSON-CSF.

Les conclusions qui peuvent être tirées à la suite de trois expériences sont les suivantes :

- l'utilisation des méthodes SID pour coupler des simulations existantes résout les problèmes d'échange de données, de format et des différences de système d'exploitation, mais pas les problèmes de cohérence entre bases de données et de modèles,
- les tâches d'adaptation sont spécifiques à chaque couplage,
- comme les traitement SID sont coûteux en calculs, il est nécessaire de disposer d'une bonne marge de puissance, sinon des messages seront perdus dans des tampons saturés dans les couches réseaux,
- il est indispensable de disposer d'outils d'analyse des échanges sur le réseau en temps réel,
- il faut utiliser des bibliothèques d'interopérabilité déjà validées ou bien disposer d'une référence validée pour se contrôler,
- une bonne compétence en réseau et système est nécessaire en plus de la connaissance de la simulation à coupler.

LISTE DE SYMBOLES

CATS	Combined Arms Training Systems
CCTT	Close Combat Tactical Trainer
GPS	Global Positioning System
I/ITSEC	Interservice / Industry Training Systems and Education Conference
IP	Internet Protocol
ITEC	Industry Training Equipement Conference
MBONE	Multicast Backbone
PDU	Protocol Data Unit (Le message élémentaire défini par la norme IEEE 1278-1)
RNIS	Réseau Numérique à Intégration de Services (ISDN)
SID	Simulations Interactives Distribuées
SIMAN	Simulation Management
STOW-E	Synthetic Theater of War - Europe
TCP	Transmission Control Protocol
UDP	User's Datagram Protocol

INTRODUCTION

Au début des années 90 THOMSON-CSF a commencé à ressentir le besoin de coupler entre elles des simulations. En ce qui concerne les simulateurs d'entraînement, le couplage permet l'entraînement collectif de l'équipe de base telle que le peloton de char ou la patrouille aérienne, avec une totale interaction entre les individus qui composent cette équipe. Avec plus de simulateurs on pourra mettre sur pied des exercices plus importants (par exemple CATS en Grande Bretagne ou CCTT aux Etats Unis). Pour les simulations technico-opérationnelles le couplage permet d'augmenter le réalisme de l'environnement utilisé pour valider un système. Comme aucune simulation isolée ne couvre la totalité des entités présentes sur un théâtre d'opération, le seul moyen de construire des simulations réaliste à grande couverture est de coupler des simulations. Après une phase d'investigation, THOMSON-CSF a reconnu l'intérêt d'utiliser les méthodes SID et en 1992 la décision de développer un outil Thomson à été prise comme méthode d'acquisition d'expérience et de savoir faire, pour pouvoir développer les fonctionnalités spécifiques dont le groupe pourrait avoir besoin et aussi parce qu'à l'époque aucun produit commercial n'était disponible en France ou en Europe.

RECENSEMENT DES BESOINS

Le recensement des besoins a fait apparaître les caractéristiques suivantes :

Paper presented at the AGARD FVP Symposium on "Flight Simulation — Where are the Challenges?", held in Braunschweig, Germany, from 22-25 May 1995, and published in CP-577.

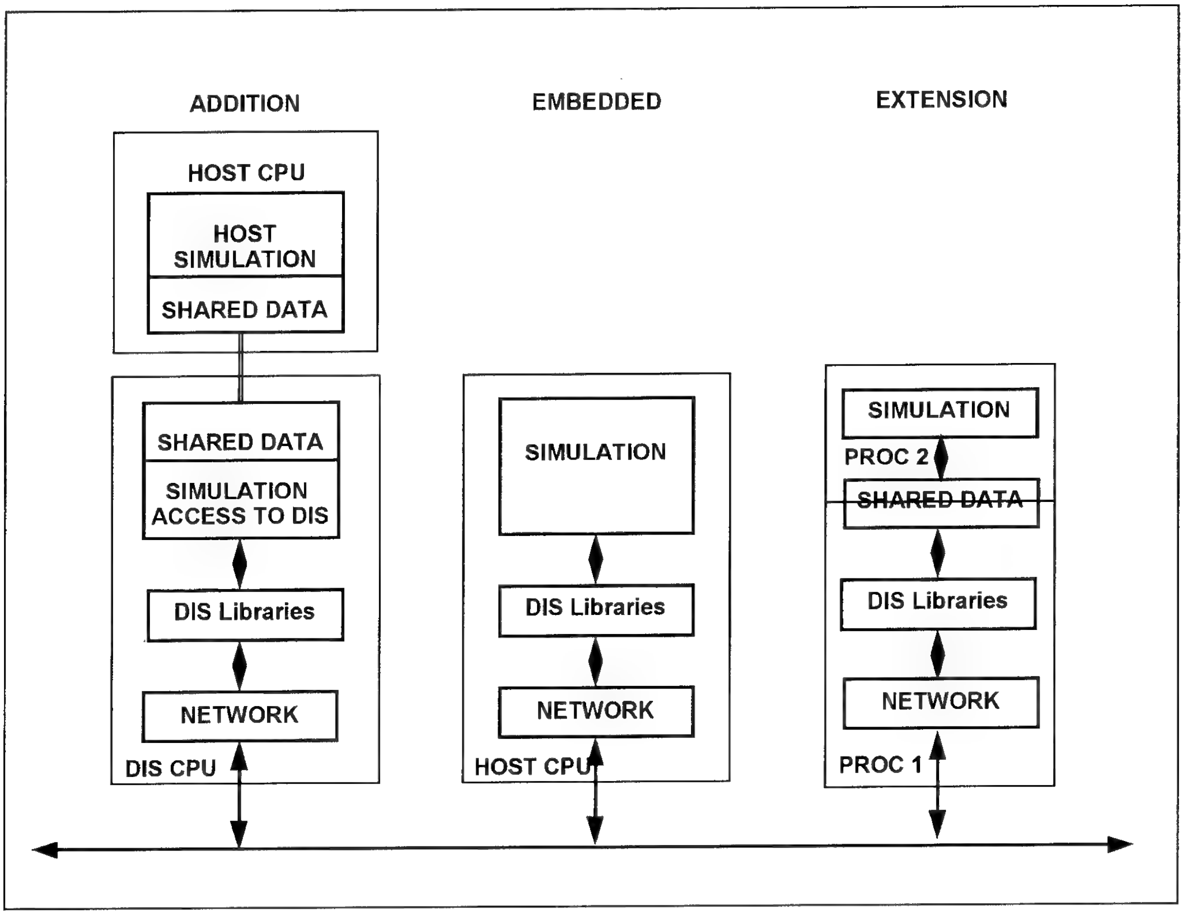

Figure 1 : Les 3 méthodes d'implémentation de bibliothèques SID

Simulations à coupler :

- Les simulateurs d'entraînement avec homme dans la boucle et un fonctionnement temps réel,
- Les simulations d'étude dont l'éventail va de la simulation très détaillée, comme par exemple la restitution d'une forme d'onde jusqu'à des simulations très globales de théâtre. En général ces simulations ne sont pas temps réel, certaines sont à pas de temps, d'autres sont événementielles,
- le besoin principal est d'abord de récupérer l'existant, il n'est pas envisageable de réécrire des simulations pour les coupler et d'attendre que de nouvelles soient crées pour bénéficier des avantages du couplage.

Un certain nombre de contraintes sont aussi apparues à cette phase de l'étude :

- particulièrement dans le cas des simulateurs d'entraînement, beaucoup de configurations de calculs auraient été très coûteuses à faire évoluer pour satisfaire les besoins en puissance de calcul requises par le couplage et les connections à des réseaux de communications,
- les simulations existantes ont été développées sur une très large variété de machines, de langages et de Systèmes d'Exploitation et il était donc impossible de développer une version de l'outil pour chacun de ces cas.

CHOIX D'ARCHITECTURE

Les contraintes ci-dessus mènent à des premiers choix d'architecture :

- les logiciels d'interopérabilité doivent pouvoir être indépendants de la machine et du système d'exploitation de la simulation à coupler. Ce qui veut dire que dans certains cas ces logiciels ne pourront s'exécuter sur la machine de simulation mais qu'ils devront être implémentés sur des machines séparées. Cette décision a été prise d'autant plus facilement qu'il existe sur le marché plusieurs offres de systèmes de mémoires réfléchies permettant à plusieurs calculateurs de type différents de partager une même zone mémoire. Tous ces dispositifs sont uniquement matériels et ne nécessitent pas l'emploi de logiciels de communications, les performances d'échange sont telles que en général on peut négliger les temps de transfert et assurer un fonctionnement synchrone entre machine de simulation et serveur d'interopérabilité. Certains de ces dispositifs sont même capables d'assurer les conversions d'ordre des octets dans un mot (Poids forts en tête, Poids faibles en tête). Ce qui mène aux trois possibilités suivantes :

- Addition,
- Extension
- Intégration (Voir figure 1)

THOMSON-CSF a donc pris la décision de développer les logiciels d'interopérabilité en C et sous UNIX "temps réel". Le choix du langage C a été fait parce que c'est celui qui permet le plus facilement de s'interfacer à des langages anciens comme le Fortran ou à des langages de haut niveau comme ADA ou le C++.

UNIX s'est imposé parce que c'est le système d'exploitation le plus largement répandu. Les fonctionnalités "temps réel" définies par la norme POSIX 1003.13 avaient été jugées nécessaires pour maîtriser correctement les ressources de la configuration. Malheureusement à cette date aucune version temps réel n'était disponible pour les stations de travail les plus couramment employées dans les laboratoires. Ce qui nous a obligé de commencer nos développements avec une version standard d'UNIX.

CHOIX D'IMPLEMENTATION

Pour satisfaire l'impératif de récupération maximum des simulations existantes et pour obtenir un outil aussi universel que possible, les principes suivants ont été retenus :

- comme l'entretien des positions présuppose un déroulement continu du temps, les simulations événementielles devront être adaptées pour fonctionner selon le mode "à pas de temps". Cela impose la gestion d'un événement supplémentaire, le déroulement d'un pas de temps,
- toutes les opérations d'entretien de position, de datation, d'extrapolation, de seuillage, de changements d'axe et/ou d'unités pour passer des axes et unités de la simulation aux axes et unités spécifiées par la norme doivent être assurées par les logiciels d'interopérabilité,
- les logiciels d'interopérabilité entretiennent une base de donnée de la situation globale à partir des PDUs (Protocol Data Unit) reçus de l'extérieur et des mises à jour fournies par la simulation hôte. La simulation hôte accède en lecture et en écriture selon ses besoins propres. On obtient ainsi une structure de serveur (voir figure 2),
- à cause de la très grande diversité des organisations de données des simulations utilisées, il a été décidé d'accéder à cette base de donnée entité par entité, événement ou commande par commande, au moyen de bibliothèques de fonctions de lecture ou d'écriture,
- comme les PDUs de type Etat sont émis systématiquement, ils sont moins importants que les PDUs de type gestion de la simulation ou du type événement comme le tir ou la détonation. En conséquence la priorité de traitement doit être assurée pour ces catégories. Pour cela nous les séparons et traitons les PDUs d'état après avoir terminé le traitement des PDUs de gestion ou événement,
- le serveur d'interopérabilité doit se synchroniser avec le cycle de la simulation hôte pour assurer la cohérence des opérations d'entretien et de datation des PDUs (voir figure 3),
- la plupart des simulations d'étude ne sont pas cadencées de manière régulière, les calculs recommencent dès que possible. Le serveur d'interopérabilité doit offrir des services de cadencement analogues à ceux des moniteurs temps réel des simulations temps réel (voir figure 4).

FILTRAGE

Pour diminuer les échanges inutiles entre la simulation et le serveur d'interopérabilité les principes suivants ont été mis en oeuvre :

- l'accès à une entité en lecture ou sa mise à jour en écriture doit pouvoir se faire seulement sur une partie de la structure du PDU correspondant. En effet une partie importante des champs du PDU véhicule des informations normalement invariables au cours du temps. Ce sont les champs Entity Type, Marking, Guise, etc. Cette approche a été reprise dans la proposition d'un PDU changement d'état qui ne transmettrait que les changements du PDU (Ref 1)
- l'accès doit pouvoir se faire selon des critères de nature afin de permettre à la simulation de n'accéder qu'aux entités qui l'intéressent. Ainsi une simulateur de combat Air-Air ne s'intéressera pas aux entités n'appartenant pas au domaine air ou au domaine munitions. L'emploi de critères de nature permet aussi de faire des tris.
- le serveur d'interopérabilité doit pouvoir filtrer les PDUs par nature. Ceci permet par exemple, à une simulation qui représente un système sans détecteur radar de ne pas recevoir les PDUs Transmitter.

Nous avons aussi identifié le besoin d'un système de filtrage en distance pour ne recevoir que les entités situées dans le domaine de perception de la simulation hôte. En effet le couplage de plusieurs simulations a en général comme conséquence d'augmenter le nombre d'entités dans l'environnement. Le traitement des entités hors du domaine de perception représente une charge de calcul inutile. Ce filtrage pourrait être fait par le logiciel d'interopérabilité ou par la couche d'adaptation. Le filtrage au niveau du serveur d'interopérabilité est plus efficace en terme de charge de calcul, puisque il est fait au moment de la réception du PDU et qu'ensuite il n'y a plus d'entretien.

Néanmoins ce filtrage n'est pas toujours suffisant, en effet les simulations ne peuvent traiter qu'un nombre limité d'entités. Ces simulations en autonome ont un générateur d'environnement qui respecte les limitations du système. Par contre une fois couplées, même après un premier filtrage en distance, l'environnement peut dépasser les capacités du système. Il faut donc prévoir des filtrages complémentaires spécifiques de l'application, par exemple en ne retenant que les entités les plus proches ou bien celles situées dans un secteur privilégié. Ceci ne peut être fait qu'au niveau de la couche d'adaptation.

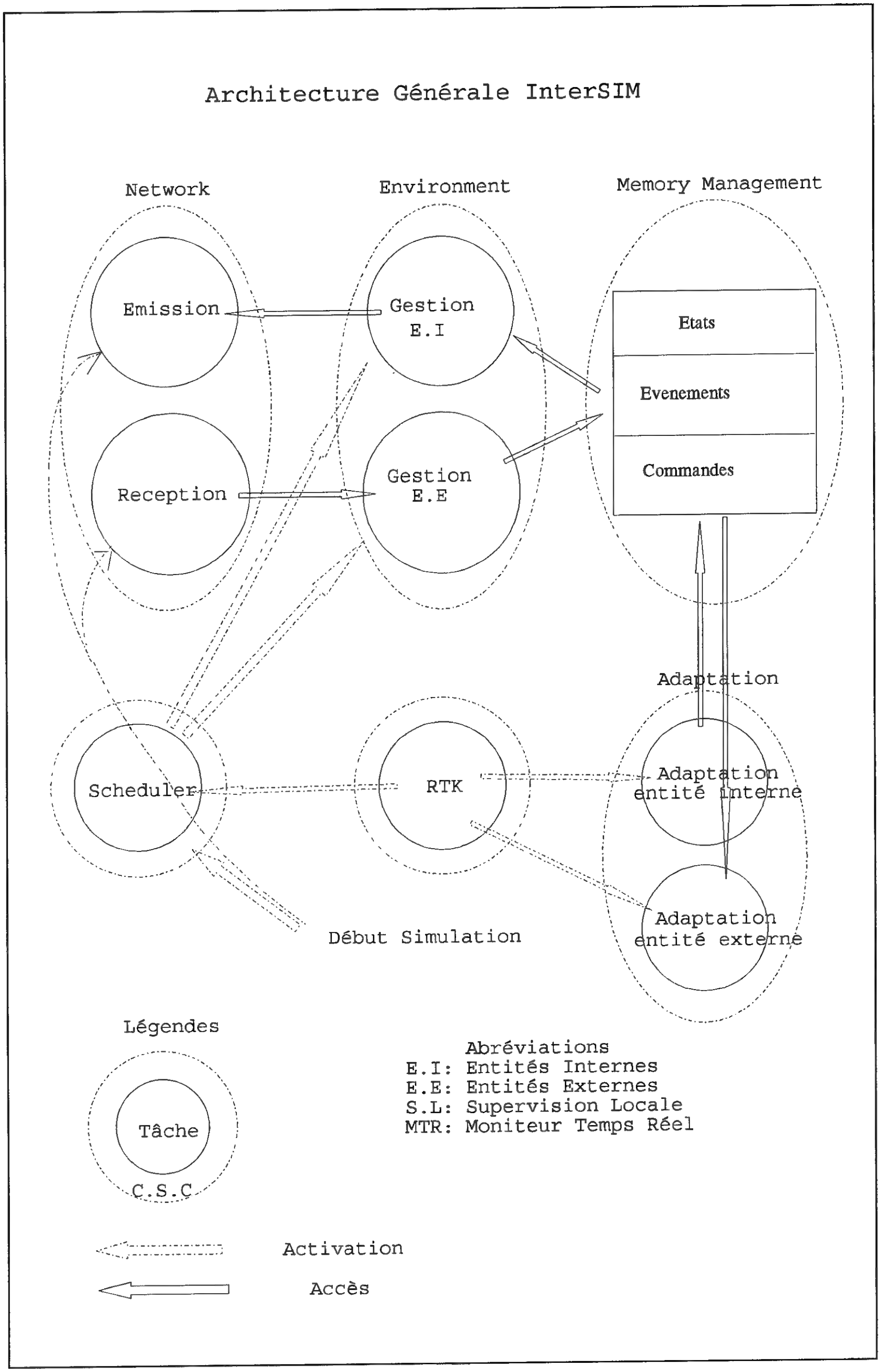

Figure 2 : Architecture générale d'***InterSIM***

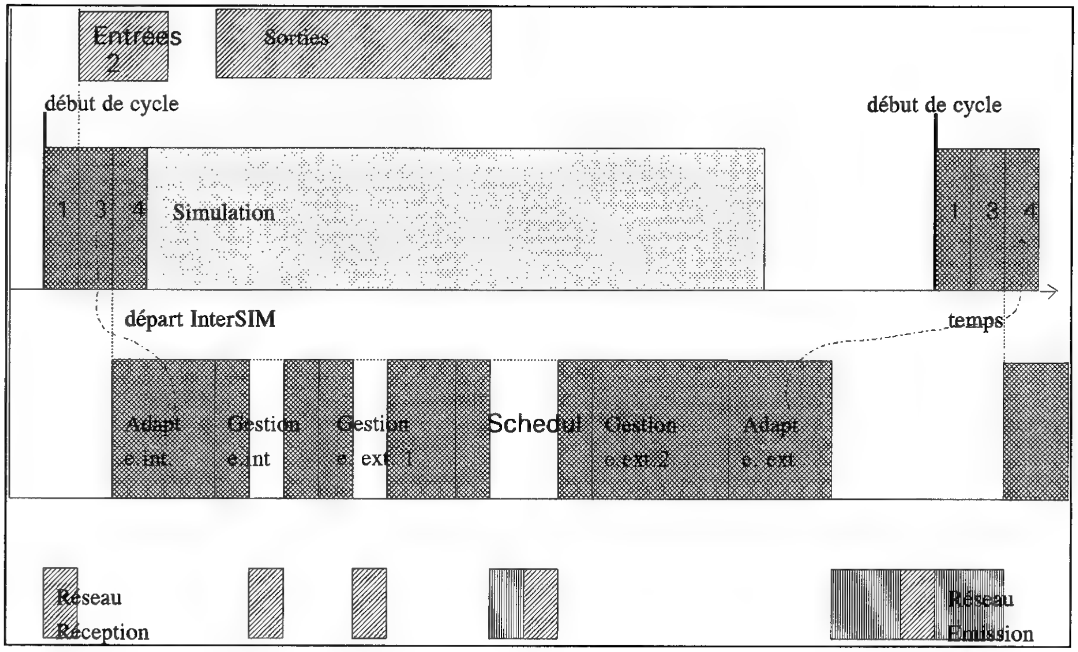

Figure 3 : ***InterSIM*** synchronisé par la simulation hôte

Entités Internes :	Entités gérées par la simulation hôte
Entités Externes :	Entités reçues par la simulation hôte
Entités externes 1 :	PDUs de type Evénement ou Commande. Ces PDUs doivent être traités dès la rédeption, sinon ils seront perdus.
Entités externes 2 :	PDUs de type Etat. Leur traitement peut être retardé.

La tâche d'adaptation des Entités Externes est activée systématiquement par une minuterie et peut interrompre la tâche de gestion des Entités Externes, de façon à disposer de données à jour pour le prochain cycle de simulation.

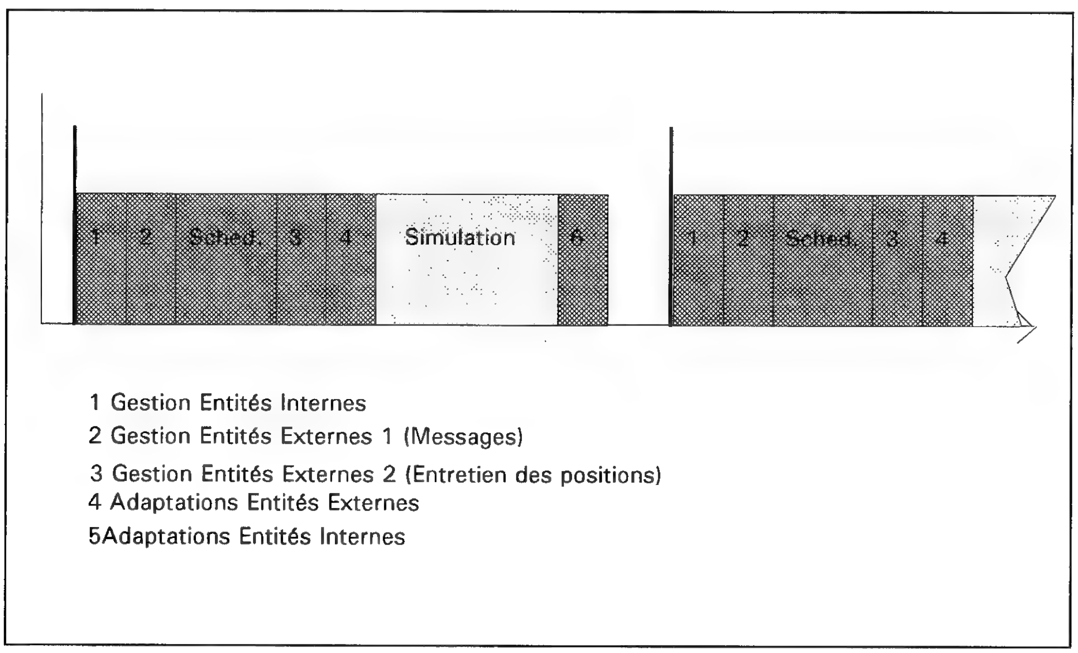

Figure 4 : ***InterSIM*** synchronisant la simulation

Une autre méthode intéressante de filtrage a été suggérée par plusieurs concepteurs. Cette méthode consiste à employer l'adressage Diffusion de Groupe (Multicast) prévu par les protocoles IP et à affecter un groupe à chaque zone géographique. Chaque simulation inscrit le PDU qu'elle envoie dans le groupe correspondant à sa zone géographique et souscrit aux groupes correspondants aux zones qu'elle est capable de percevoir. cette méthode ne pouvait pas être implémentée jusqu'à récemment parce que le mode Diffusion de groupe était peu disponible dans les stations de travail et pas du tout dans les routeurs. Le développement des vidéoconférences sur le réseau Internet utilisant le système MBONE et l'introduction de l'Assynchroneous Transfer Mode (ATM) sont en train de déclencher une offre de produits en forte croissance. L'expérience Synthetic Theater of War Europe (STOW-E) de novembre 94 a utilisé le mode Diffusion de Groupe. L'emploi de ce mode est prévu dans la version suivante de la norme IEEE en cours de ratification.

CHOIX DES PDUS.

La norme IEEE 1278 prévoit des PDUs (Protocol Data Units) pour :

- décrire l'aspect extérieur des entités, tel qu'il pourrait être perçu par des capteurs. Dans cette catégorie on trouve :
  - le PDU Entity State qui décrit la position et l'aspect visuel des entités,
  - le PDU Emitter qui décrit l'émission électromagnétique rayonnée par une entité,
  - le PDU Laser qui décrit la zone illuminée par un désignateur laser,
  - le PDU Transmitter qui décrit un émetteur radio ainsi que le PDU signal qui achemine le contenu de l'émission,
- décrire le tir d'une arme (PDU Fire) et l'explosion de la munition tirée (PDU détonation),
- signaler la collision d'une entité avec une autre avec un élément du terrain (PDU Collision). Le but de PDU est de signaler aux simulations réceptrices qu'elles doivent modifier l'entretien des positions des entités en collision. La simulation réceptrice doit arrêter d'extrapoler et figer l'entité en collision en attendant un nouveau PDU Entity State pour cette entité,
- permettre la simulation des opérations logistiques en décrivant les échanges entre entités demandeuses de services d'approvisionnement ou de réparations et les entités capables d'offrir ces services. Ce sont les PDUs Repair ou Ressuply, offer, request acknowledge. Ces PDUs servent à décrire les quantités échangées et à simuler les délais impliqués par ces opérations.
- gérer la simulation en créant ou supprimant des entités, démarrer, arrêter la simulation. Ce sont les PDUs de la famille SIMAN ,
- de plus il a été reconnu que les besoins des simulations d'étude rendaient nécessaires l'accès à des valeurs internes, la possibilité de modifier des paramètres. La norme a donc prévu les PDUs Set Data, Send Message....

Comme le PDU de collision n'est utile que dans les simulations d'environnement terrestre avec visuel et que la logistique n'était pas utilisée dans les simulations THOMSON-CSF, nous avons décidé dans une première étape de ne pas les implémenter. Depuis le besoin est apparu et il a fallu les rajouter.

En plus de ces PDUs THOMSON-CSF a ajouté des PDUs supplémentaires non prévus par la norme pour gérer la synchronisation des horloges et le temps non réel. THOMSON-CSF utilise ces PDUs pour :

- synchroniser les horloges de calculateurs dont les OS ne prévoient pas de fonction de synchronisation sur une horloge de référence,
- synchroniser des simulations non temps réel présentant une charge de calcul fortement variable.

SYNCHRONISATION DES HORLOGES

Un des principes de base de la norme SID, c'est l'entretien par extrapolation des positions des mobiles. En théorie cette extrapolation se fait en intégrant la vitesse et éventuellement l'accélération sur l'intervalle de temps séparant l'instant où l'émetteur a calculé le vecteur d'état et l'instant ou la simulation émettrice fait un nouvel accès à la position extrapolée. Cette extrapolation se fait selon la formule générale suivante :

$$\vec{\mathbf{P}}_{t1} = \vec{\mathbf{P}}_{t0} + \vec{\mathbf{V}}_{t0}(\mathrm{T1-T0}) + \frac{1}{2}\vec{\Gamma}_{t0}(\mathrm{T1-T0})^2$$

Formule 1 : Extrapolation de la position à partir de la vitesse et de l'accélération.

où :

- T_0 = heure de validité du PDU
- T_1 = heure courante

Et pour cela la norme SID a prévu que chaque PDU soit accompagné d'une estampille de date (time stamp), donnant l'heure de validité du PDU. Mais pour que le calcul ci dessus soit juste, il faut que les horloges de la simulation émettrice et réceptrice soient synchronisées entre elles. La norme SID permet à la simulation émettrice d'estampiller soit à partir de l'heure en Temps Universel, soit d'utiliser une référence locale.

Pratiquement lors des démonstrations faites lors des conférences ITEC ou I/ITSEC seule la référence locale était utili-

sée par simplification. Dans ce cas deux alternatives sont possibles :

- faire l'hypothèse que les horloges locales sont suffisamment proches pour que l'on puisse négliger leur différence et la formule 1 continue à s'appliquer.
- faire l'hypothèse que la différence entre les horloges est plus grande que la somme des temps de codage à l'émission, transfert sur le réseau et codage à la réception. Dans ce cas, il faut à la réception du PDU remplacer l'estampille émise par l'heure locale de réception.

Dans un réseau local sans synchronisation particulière des horloges la deuxième hypothèse est la plus valable. En effet les temps de transfert sur un réseau local non saturé sont faibles, et il est aussi possible de compenser les temps de codage et de transfert en soustrayant quelques dizaines de millisecondes à l'heure locale de réception. Mais cette méthode oblige à prévoir un moyen de changer cette correction parce qu'elle change d'un exercice à l'autre en fonction du réseau et de la charge.

Dans le cas d'un couplage au moyen d'un réseau à longue distance les temps de transfert peuvent être beaucoup plus importants et variables, par exemple dans le cas de réseau à commutation de paquets. De même certaines simulations d'étude réclament une très bonne synchronisation des horloges pour assurer une bonne précision. Une erreur de quelques dizaines de millisecondes provoque une erreur de quelques dizaines de mètres sur la position d'un mobile évoluant à Mach 3. De plus des exercices de grande amplitude comme STOW-E ont montré qu'il était quasi impossible de fusionner des enregistrements faits sur chaque site s'ils n'étaient pas estampillés en Temps Universel.

Dans ce cas les simulations doivent utiliser une référence de temps unique. Cette référence peut être obtenue par l'utilisation d'un service de distribution de l'heure s'il existe sur le réseau et s'il a la précision requise. Une autre méthode est l'emploi d'une référence locale suffisamment précise et stable pour satisfaire la condition d'unicité. Une telle référence peut être fournie par un récepteur GPS. Il existe des cartes au format VME incorporant un récepteur GPS facilement utilisable dans un calculateur. La principale difficulté est l'installation de l'antenne qui doit avoir une vue directe des satellites GPS. Si l'on ne cherche pas une très grande précision, il est possible de synchroniser les horloges en employant la méthode de "Flaviu".

Dans cette méthode un site maître délivre l'heure aux esclaves à leur demande. Le simulateur "A" est responsable de la référence. Le simulateur "B" se synchronise sur "A" au moyen d'un échange de PDUs, extension aux protocoles SID (Requesting Time PDU, Servicing Time PDU).

La formule de synchronisation est :

$$H_t = \frac{H_{Bt2} - H_{Bt0}}{2} + H_{refAt1}$$

où :

- t_0: heure locale pour B de l'émission du PDU Requesting Time
- t_1: heure de référence de A d'émission du PDU Servicing Time PDU
- t_2: heure locale pour B de réception du PDU Servicing Time .

FONCTIONNEMENT EN TEMPS NON REEL

La norme SID prévoit explicitement le fonctionnement en temps réel, qui s'impose bien évidemment pour les simulations avec homme et/ou du matériel réel dans la boucle. Cependant un grand nombre de simulations ne sont pas temps réel et il serait intéressant de pouvoir les coupler entre elles en utilisant les méthodes des Simulations Interactives Distribuées.

Ceci est possible en utilisant la méthode un facteur d'échelle variable pour le temps (Ref 2). Dans ce mode de fonctionnement on définit :

- un facteur de dilatation du temps, rapport Temps Simulé/Temps Universel,
- une durée de temps simulé (Time Slice) pendant laquelle ce facteur de dilatation sera utilisé.

Chaque simulation démarre et va au bout de ce temps simulé, passe en mode gel et fournit à la station de supervision un Time_Slice_ACK PDU qui contient l'heure universelle d'émission de ce PDU et le ratio K = Temps simulé / Temps CPU consommé.

Quand toutes les simulations ont terminé et renvoyé leurs comptes-rendus, la station de supervision calcule un nouveau facteur de dilatation et une nouvelle tranche de temps simulé à exécuter en fonction des comptes rendus et renvoie ces informations aux simulations au moyen du PDU Time_Slice.

A l'intérieur de cette tranche de temps simulé, plusieurs pas de simulation s'exécuteront. Pour réduire au minimum la désynchronisation entre les simulations "lentes" et les simulations "rapides", le Moniteur Temps Réel des bibliothèques d'interopérabilité relance la simulation de façon à ce qu'elle recommence son prochain cycle au bout d'un temps égal à au moins :

$$DT = \text{Pas de temps simulé} \times K$$

SECURITE.

L'emploi de PDUs normalisés est potentiellement une source d'insécurité. Même si les données véhiculées ne contiennent pas directement les caractéristiques des entités simulées, toute personne qui a pu écouter le réseau est capable de reconstituer les trajectoires, les performances, les distances d'engagement etc. Si les échanges se font sur un réseau non protégé il faut employer des techniques de cryptage. Deux types de méthodes sont possibles. On peut crypter par logiciel les PDUs au moment de leur calcul, juste avant le passage

dans les couches réseau, ce qui laisse en clair les en-têtes IP utilisées par les fonctions de routage. On peut aussi utiliser des chiffreurs placés à la sortie du calculateur, ce qui économise de la puissance de calcul. Par contre il faut utiliser des chiffreurs qui comprennent les en-têtes réseau pour les laisser en clair. De même il faut utiliser des chiffreurs permettant le mode diffusion vers plusieurs destinataires utilisant une même clé.

Les techniques logicielles sont coûteuses en temps calcul, mais elles sont faciles à mettre en oeuvre. C'est une méthode intéressante pour "cacher" seulement quelques entités sensibles dans un environnement plus large et sans sensibilité particulière.

Le chiffrage, s'il est systématique, protège aussi contre les intrusions en cours d'exercice. Plus généralement il faudrait n'accepter à la réception que les PDUs émis par des machines identifiées comme participant à l'exercice.

Finalement nous avons conclu que les besoins étaient trop divers et les solutions très dépendantes de la configuration matérielle et réseau pour pouvoir proposer une réponse standard. Notre approche est d'utiliser un réseau local protégé et dans le cas de liaisons à longue distance de résoudre le problème au niveau des passerelles. Ceci a l'avantage de ne pas imposer de contraintes particulières au niveau des simulations.

LEÇONS TIREES DE L'UTILISATION DU LOGICIEL.

Ce logiciel a déjà été utilisé dans trois occasions différentes en dehors du démonstrateur de validation qui a été utilisé pour son développement.

Première expérience.

Une première fois, dans une version préliminaire et à titre de démonstration, lors du couplage de deux simulateurs d'avions d'arme Mirage 2000C. Ces simulateurs sont situés sur les bases aériennes de Cambrai et Orange, soit à plus de 800 Km (500 Miles). Les principaux enseignements ont été :

- l'utilisation de liaisons RNIS à bande étroite est une solution pratique pour des liaisons non permanentes. On peut multiplexer plusieurs lignes entre elles pour atteindre le débit souhaité. Une fois établie la liaison est permanente de bout en bout et le délai de transmission est très faible, au moins pour ces distances. Le out de l'abonnement est modique, comparé aux lignes permanentes louées, et on ne paie que l'utilisation.
- pour des simulateurs de vol l'aspect visuel est primordial. Le saut de position ou d'attitude qui se produit à la réception d'un nouveau PDU est parfaitement visible pour les simulateurs en dôme. Il faut donc lisser les valeurs de position et d'attitude en sortie des programmes d'entretien. Il faut employer des méthodes de lissage qui n'introduisent pas d'erreurs résiduelles car celles ci sont détectées lors des vols en formation. Une erreur résiduelle de quelques mètres est visible, car chaque pilote voit l'autre en "arrière" et attend qu'il le rejoigne. La méthode classique du filtre du premier ordre appliquée à une extrapolation sur la position introduit une telle erreur, puisque la position évolue constamment. Le lissage linéaire (l'erreur de position δ lors de la réception d'un nouveau PDU est annulée en n cycles en utilisant n incréments égaux δ/n) ne crée pas d'erreur résiduelle, mais il y a une discontinuité de vitesse qui est quelquefois visible. Un filtre du deuxième ordre avec avance de phase donne de bons résultats. Pour l'attitude, comme celle ci n'évolue pas constamment, un lissage du premier ordre suffit.

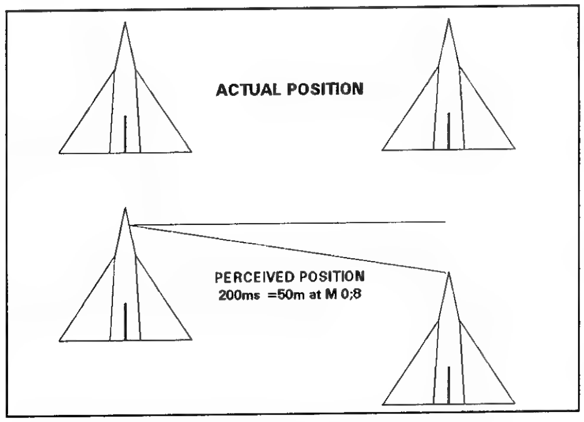

Figure 5 : Retard de position

- l'extrapolation d'un paramètre pour compenser le délai de transmission peut créer des transitoires perturbants lorsque ce paramètre peut varier de manière important en un laps de temps du même ordre que le délai de transmission (voir figure 6). C'est le cas par exemple de la vitesse de roulis qui peut atteindre, sur un avion d'arme, des valeurs très élevées en très peu de temps. L'extrapolation de cette vitesse sur une durée égale au délai mène à des dépassements car en réalité la vitesse s'est annulée en un temps plus court. Cet effet a été évité en n'extrapolant plus le roulis. Cet effet illustre une des limitations de la méthode SID. La méthode ne s'applique bien que pour transmettre des phénomènes dont les constantes de temps sont supérieures aux délais de transmission.

Deuxième expérience.

Pour cette occasion le logiciel a été utilisé pour une expérience de couplage de simulations qui a eu lieu pendant la conférence ITEC de 1994. Cette fois ci le but était de coupler un simulateur de radar aérien développé par LINK-MILES à l'environnement crée par les autres simulations. C'était aussi la première fois que ce logiciel était confronté à d'autres logiciels d'interopérabilité. Les enseignements qui ont été tirés de cette expérience sont :

- le portage du logiciel, originellement développé sur SUN, sur machine Silicon Graphics a été fait sans aucun problèmes, justifiant ainsi le choix d'UNIX comme système d'exploitation,

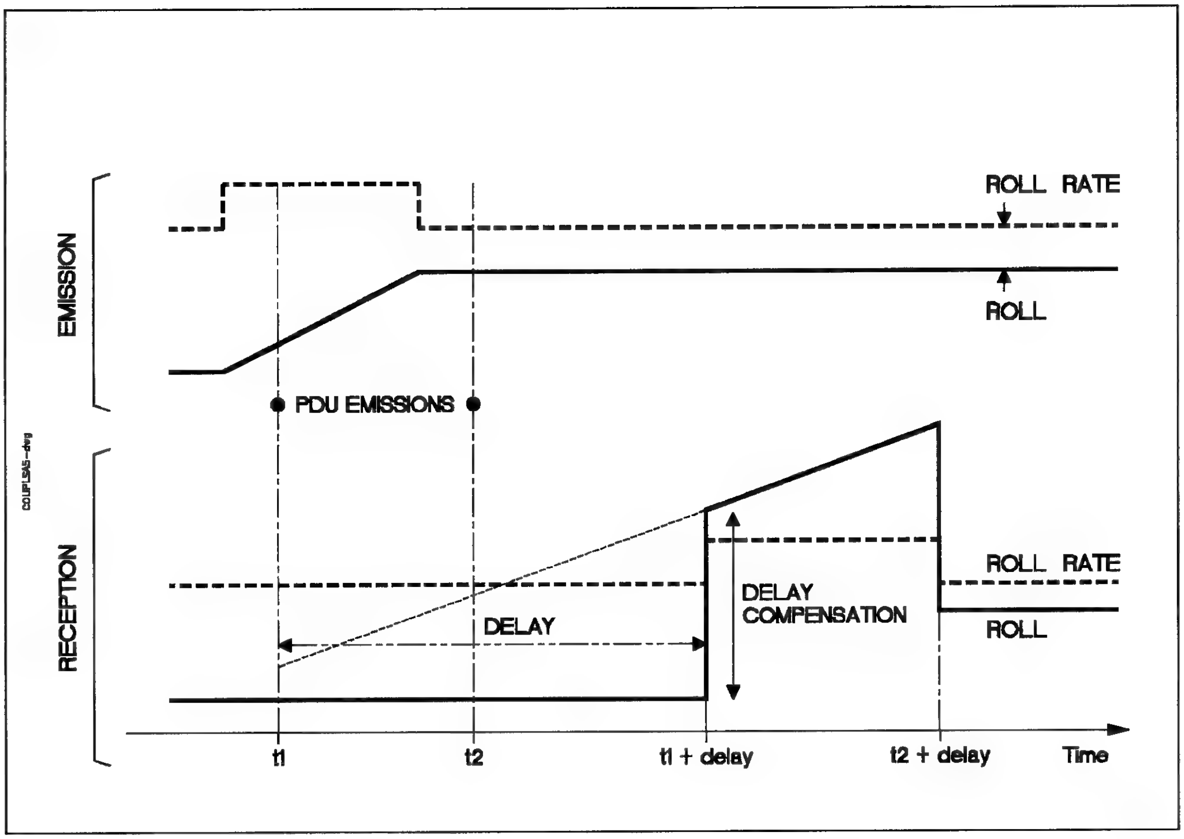

Figure 6 : Dépassement pendant une extrapolation

- la mise au point complète d'un logiciel de ce type ne peut se faire qu'en utilisant un serveur d'interopérabilité de référence. A cette occasion nous avons découvert plusieurs erreurs de formatage et de programmation des algorithmes d'estime. Ces erreurs nous avaient échappé parce qu'elles étaient masquées par des erreurs symétriques à la réception,
- il faut prévoir les moyens de changer rapidement les adresses réseau, les ports IP/UDP, les classes d'adressage de la machine hôte pour s'intégrer dans le schéma d'adressage d'une expérience de couplage,
- l'utilisation d'outils permettant la visualisation en temps réel des PDUs qui circulent sur le réseau facilite beaucoup la mise au point. Les outils d'enregistrement conçus pour l'analyse à posteriori ne sont pas utilisable pour une mise au point.

Troisième expérience.
Cette expérience a consisté à coupler des simulations de théâtre mettant en oeuvre des simulations de systèmes de défense antiaérienne avec leurs systèmes C2, opposées à des simulations de raids aériens. Le but était de répartir ces simulations sur plusieurs machines pour augmenter la puissance de calcul disponible par opposition à l'utilisation d'une machine centralisée. Contrairement aux expériences précédentes ce couplage met en oeuvre un grand nombre d'entités.

Une autre caractéristique est aussi que les simulations de C2 n'avaient prévu par simplification aucun contrôle de la qualité de la transmission, parce que dans une exécution centralisée aucun raté de transmission n'était à redouter. Les principaux enseignements ont été :

- la perte de messages, si elle n'est pas trop fréquente, est acceptable pour les messages d'état grâce à la robustesse de la méthode. Par contre des pertes, même faibles, perturbent la simulation des systèmes C2. Pour fiabiliser la transmission des messages C2 deux méthodes ont été envisagées, soit utiliser le protocole TCP/IP, soit faire contrôler la transmission par le logiciel d'interopérabilité. D'une part TCP/IP offre la garantie de résultat recherchée, mais est coûteux en ressources et n'offre que des transmissions en point à point. D'autre part UDP/IP est plus rapide, plus simple à utiliser et permet l'emploi du mode Diffusion de Groupe. Le contrôle de la réception par acquittement des messages de type SIMAN ou logistique est prévu dans la norme. Cette méthode a finalement été retenue, aussi parce qu'elle ressemble à celle utilisée dans de nombreux protocoles C2. Mais les performances ne permettront pas toujours de respecter les très courts délais utilisés dans certains protocoles. Nous nous retrouvons encore une fois devant la principale limitation de la méthode, l'impossibilité de transmettre des données évoluant rapidement.

- le couplage a été fait en utilisant l'UNIX standard parce que le seul disponible sur les machines cibles, et au début nous avons relevé de nombreuses pertes de messages. Après investigation nous avons découvert que ces pertes n'étaient pas dues à des collisions sur le réseau, mais à des tampons saturés dans les couches réseau. La raison en était que le partage équitable des ressources, principe de base d'UNIX, permettait à la simulation de créer plus d'entités à chaque pas que les couches réseau ne pouvaient en traiter dans le laps de temps alloué par UNIX. Pour corriger ce défaut nos avons modifié l'ordonnancement des tâches de manière à attendre la libération des tampons avant de recommencer un nouveau pas de simulation. L'emploi d'un UNIX temps réel nous aurait permis de résoudre ce problème beaucoup plus simplement en utilisant les mécanismes de priorité. Néanmoins nous devons rester conscients qu'une simulation qui crée de nombreux PDUs induit forcément une forte charge sur les couches réseau.

- le nombre de messages à traiter par les couches réseau pourrait aussi être réduit en utilisant le mécanisme de concaténation des PDUs. En général un PDU a une taille inférieure à celle d'une trame IP sur Ethernet; on peut donc concaténer plusieurs PDUs dans une même trame et réduire ainsi le nombre de trames à traiter.

- ces simulations de théâtre utilisent des pas de calculs relativement importants, typiquement 5 sec, mais lors du calcul de la distance de passage d'un missile de positions intermédiaires sont nécessaires. L'estime systématique d'un pas sur l'autre ne permettait pas de calculer ces positions intermédiaires. Il a donc été décidé d'offrir une fonction de lecture de position estimée pour la date fournie par l'utilisateur.

CONCLUSION.

Toutes ces expériences nous ont mené aux conclusion suivantes :

- les protocoles SID permettent effectivement de coupler des simulations déjà existantes sans obliger à des modifications importantes de celles ci, pourvu que leur organisation initiale ait déjà bien séparé la génération d'environnement de la simulation proprement dite. dans ce cas il est facile de remplacer la génération originelle d'environnement par l'environnement crée par les autres simulations. Néanmoins les méthodes SID ne résolvent que les problèmes de transmission de données, mais pas les problèmes de cohérence des bases de données terrain, des modèles de surface équivalente radar ou des bases de données de signatures restent à résoudre.

- SID est une méthode saine pour coupler des simulations de grande taille et permet de remplacer un simulation par une autre ce qui donne une grande souplesse d'emploi,

- il est nécessaire de développer les adaptations nécessaires au filtrage de l'environnement pour l'adapter aux possibilités de la simulation. Ceci ne peut être fait qu'après avoir clairement défini les scénarios et évalué le trafic. Chacune de ces adaptations est spécifique à chaque exercice de couplage.

- Les protocoles SID sont générateurs d'une forte charge de calcul, les utilisateurs ont toutes les chances de devoir augmenter la configuration initiale d'une manière ou d'une autre. Une des conditions pur ne pas perdre de messages est d'avoir une bonne réserve de puissance pour absorber les pics de transmission. C'est à dire que la configuration doit être capable de traiter à chaque pas nettement plus que le débit moyen attendu. Il est à remarquer que certains papiers écrits après STOW-E recommandent de mettre en oeuvre des méthodes pour empêcher l'émission simultanées de blocs de PDUs.

- sur un réseau local le facteur limitant c'est la puissance de calcul et pas la bande passante du réseau,

- l'emploi d'outils de visualisation temps réel est indispensable à la mise au point en temps réel,

- on doit pouvoir ajuster les allocations de ressources de la configuration pour éviter les déséquilibres entre tâches. Ceci ne peut se faire qu'avec l'aide d'un spécialiste système et réseau.

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Ref 2 : Variable Scaling Time Implementation. Jean Pierre Faye and David Taylor. 10th DIS Workshop.

HIGH FIDELITY, MOBILE, NET WORKABLE TRAINERS THE TRAINERS OF THE FUTURE?

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ABSTRACT

The U.S. Naval Air Warfare Center Aircraft Division Patuxent River personnel recently completed a high fidelity, low cost mobile prototype AH-1W Aircrew Procedures Trainer for the United States Marine Corps at Camp Pendleton, California. The use of recent technological breakthroughs in both super-micro computers and visual display technologies made this program possible. These breakthroughs pave the way for future OFT/APT developments. The AH-1W APT project demonstrated the application of evolving simulation technology in four areas. First, that new technologies reduce the physical size of room required to support computational requirements of WSTs. Second, newer technologically advanced COTS computers can be used in a rugged environment without any special expensive considerations. Third, existing full-size training systems could be supplemented or replaced by such small, mobile devices such as the AH-1W high fidelity trainer prototype constructed at NAWC AD. Fourth, fixed wing tactical aircraft training systems that do not require motion cueing devices are particularly attractive for this application.

Future considerations should include the use of the actual aircraft as a training system. This could be accomplished by aircraft that employ computer buses for aircraft control. This paper will survey the current possible mobile trainer configurations, and examine the use of actual tactically deployed aircraft as the basis for training systems.

LIST OF ABBREVIATIONS

DIS	Distributed Interactive Simulation
COTS	Commercial Off-The-Shelf
NAWC AD	U.S. Navy's Naval Air Warfare Center Aircraft Division
MFS	Manned Flight Simulator Facility
WST	Weapons System Trainer
OFT	Operational Flight Trainer
IOS	Instructor-Operator Station
APT	Aircrew Procedures Trainer
SMT	Small Mobile Trainer
FPT	Fleet Project Team
TNS	Tactical Navigation System

PROBLEM STATEMENT

The current need of the military is a more realistic training at a much lower, more affordable cost. In face of decreasing budgets, and ever more expensive weapon systems, the military cannot afford to continue to construct and deploy traditional trainers except at the expense of removing funding from the actual usable weapon system. The trainers of the future must support: broad geographical areas, various realistic combat conditions, provide usable and realistic experiences with weapons, improve aircrew safety, be mobile and relocate-able, and support mission rehearsal requirements.

Modern technology has produced the "Weapons Systems Trainer" or the "Operational Flight Trainer" in the U.S. Department of Defense as an answer to the added requirements placed upon simulation in training. OFTs are being used as a substitute for actual aircraft flight instruction for basic flight training. This is an expansion of the role of simulation in military training beyond the use primarily for emergency procedures training that was common only a few years ago. WSTs are used for basic flight training, but are also designed to do the additional functions required to train the student, or refresh the veteran, in delivering accurately the large amounts of ordnance carried by today's attack aircraft. WSTs have supplanted the actual live firing of modern, expensive, weapons to the extent that many pilots who have not flown in combat may

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have never fired one of the more exotic weapons that they are expected to be able to use in combat, or at best are allowed to fire one or two such weapons a year.

Modern WSTs and OFTs do a good job of training modern pilots for the threats and scenarios that they may meet in a still-hostile world, but they share one flaw that has become more apparent to air crews and training systems personnel alike: a fixed site availability and huge cost. Current WSTs and OFTs are large, building sized devices, often requiring dozens of support staff and technical crew members to ensure daily availability.

IDEAL DESIGN REQUIREMENTS

The ideal design for a mobile, high fidelity trainer would incorporate at least the following nine features:

1. Mobile, including air, land or sea deployability
2. High fidelity cockpit and visual system
3. Reuse existing software models
4. Easily adaptable to configuration changes
5. Employ COTS equipment
6. Capable of operation by flight crew without trainer system knowledge
7. Capable of operation using portable power supplies
8. Capable of operation within a short time period after a movement
9. Capable of training all procedures, both normal and emergency, found in the NATOPS, including night vision capability.

For the purposes of this paper, such a system will be called a Small Mobile Trainer (SMT).

CURRENT MOBILE SYSTEMS: AN EXAMPLE

The MFS facility is a high technology Navy asset of NAWC AD Patuxent River. MFS was selected for the prototype construction because the unique nature of the facility and the type of simulation work done there could translate directly into the AH-1W APT project.

The project requirements called for MFS to design and build two prototype APTs. The goal of the first prototype was to prove the basic concepts of a mobile high fidelity simulation, provide training on the new Tactical Navigation System, and receive fleet comments. The goals of the second prototype (currently under development) will expand on the capabilities of the first to include the new Night Targeting System and weapons delivery training. Fleet comments will also be generated on the second unit and noted when the specification is written for industry to generate more devices if required.

The MFS approach to the problem began with the development of a Fleet Project Team. The FPT consists of active and reserve Marine pilots and MFS engineers. This program was initiated in 1992. The system was designed to fit within a mobile unit complex consisting of three standard mobile units with minor modifications. These units house the deployed system. In addition, these three units serve as the shipping containers when the device is being transported. The device design called for a three channel visual system for the first device, and a four channel visual system for the second device. The final system design layout is show in Figure 1.

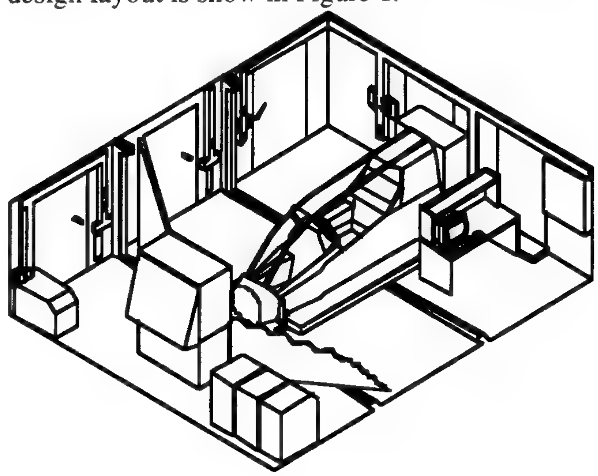

FIGURE 1
System Design Layout

Computer Architecture

The computer system chosen for the APT was the Digital Equipment Corporation's VAX Station Model 4000-90, with the VMS operating system. The MFS has had extensive experience with this type of system in past years, and the modular software systems developed there operate best with this environment. The DEC Model 90 has a Linpack Single Precision rating of 12.91 million floating operations per second (MFLOPS). This rating compares to the current

host machines of the AH-1W WST's 1.8 MFLOPS rating. To allow large amounts of space for future expansion in input/output requirements, it was decided that two Model 90s with BIT3 Corporation's Turbochannel to VME adapters would be used as the host machines for each APT.

A shared VME backplane serves as the common Input/Output system for the APT and as the path to the shared memory. One of the BIT3 VME adapters contains a daughter card populated with 2 megabytes of shared memory. The majority of accesses are performed by the airframe VAX, so its BIT3 VME card hosts the shared memory. This minimizes VME bus utilization. A FORCE 68040 VME Single Board Computer (SBC) is used to process DIS protocol data units and is also located in the VME chassis. The SBC DIS software utilizes one megabyte of the shared memory to communicate with the visual system software. In addition, the machines were equipped with Military Standard 1553 Bus interfaces for communication with actual aircraft hardware.

The host computers measure 40x20x60 Centimeters and weigh less that 75 kilograms each and mount in standard computer racks located at the rear of the cockpit. This can be compared to the room full of computers required to run the same software for the existing WSTs.

Visual System

The requirements for the APT visual image generation systems were:

- small physical size
- textured visual scenes
- ability to use existing WST databases
- low cost per channel
- ability to produce night vision device imagery.

The system selected was the Evans and Sutherland ESIG-2000 image generation system, which fulfilled all the above requirements. In addition, the system is capable of 60 Hz operation for minimal transport delay, laser range finding, and up to 63 moving models. This system is capable of using areas of the visual databases developed for the WSTs.

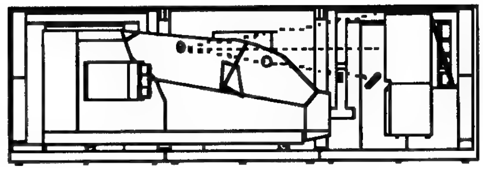

FIGURE 2
Forward Display Field of View

This front display provides an 18.4° vertical field of view, with 9.4° of view up from the horizon and 9.0° field of view below the horizon, with a 24.3° horizontal field of view. This provides side fields of view (FOV) of 8.4° up FOV, 26° down FOV, and 45.7° horizontal FOV. This results in a total of 115.6° horizontal FOV.

The entire system operates on one 50 ampere 120/208 Volt, 3 phase 60 Hz external power supply. The mobile unit complex cooling and heating equipment requires two additional lines. This amount of power can be generated by several U.S. Military standard mobile generators. The APT mobile units contain power conditioning and power interruption protection equipment to allow operation and protection to the system from any quality of power supply.

The user interface consists of a US patented video switching and software system that allows the IOS "point and click" control screens to be displayed on the forward field of view at the touch of the cockpit mounted IOS controller. The training time to teach a novice aircrew how to use this system for effective training has been found to be under one hour.

Summary of the Prototype

Together with the above visual and computer systems, the prototype consists of an actual nose section of a stricken AH-1T that was cut down and modified to fit within the mobile units. The cockpit section was then populated with gauges, switches and panels all of which were NVG compatible. The aircraft hardware utilized included the sticks, collective and control linkages, TNS, HUD, Full Functional Signal Processor and the TOW/Hellfire Control. All the hardware above combined made an exact copy of the AH-1W TNS cockpit area.

When it came time to interface hardware and software, MFS started with the WST software as a proven baseline. The code was then rehosted to run on DEC computers and to use the MFS lab

executive and simulation control software. Only the models dealing with the new TNS had to be designed and written from scratch.

Since its delivery in September of 1994, the AH-1W APT has been scheduled 50 hours a week and has seen less then four days down time. This small amount of down time is due to a modem that MFS incorporated into the prototype to allow access to the simulation when support is needed.

Since the trainer has no motion base and proven COTS equipment, the amount of knowledge required to maintain the device is rather small. The device incorporates software driven daily readiness checks and hardware diagnostic tools. With these tools, the simulation is maintained with minor aircrew involvement.

The Navy's prototype incorporates all the desired ideals of a portable trainer. Improvements to the system could be made in the visual system by relaxing the requirement to use the mobile units in an unmodified way, or by going to a helmet mounted display system. The fleet has used the prototype for six months, and they have found it to be a very effective and reliable system.

FUTURE THRUSTS /CONSIDERATIONS: USE OF ACTUAL ASSETS AS TRAINING DEVICES

Modern aircraft (and other) weapon systems are becoming more complex and dependent on electronic data buses for displaying information. When almost all interaction between the weapon system and the operator uses a data bus it becomes possible to design training systems that use the actual aircraft themselves as the training assets. The design concept and solution that MFS has created is called "Lamprey," after the fish that attaches onto a host and remains there, using the host for movement and food.

The concept is best illustrated with an example, in this case using an F/A-18C or new F/A-18E/F aircraft. Both of these aircraft use MILSTD 1553 buses for displaying the bulk of information to the pilot. This bus is also utilized to read switches and aircraft control positions. In very simplified form, the flow path in the aircraft is shown below:

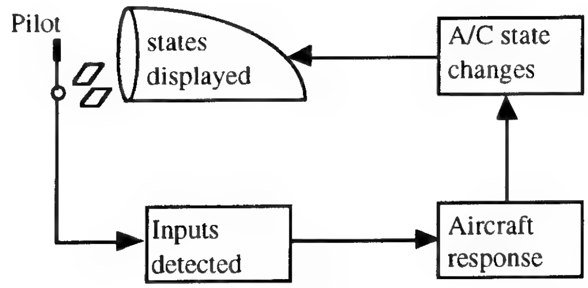

FIGURE 3
Simplistic Databus Flow Path

A static aircraft can be converted into a training system by the addition of a visual system and a host computer. The host computer would listen in on the bus traffic to detect pilot control movements and cockpit switch selections. The host computer would then, using high fidelity models, perform the usual simulation processes to calculate the new states of the aircraft and the required cockpit displays. This information would then be put back on the bus for display to the pilot/trainee by the usual aircraft displays.

The information flow would then look like:

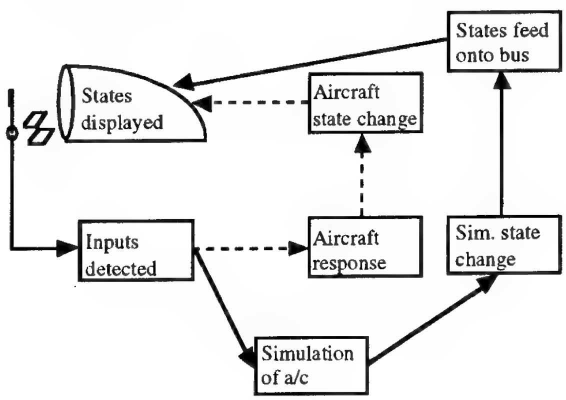

FIGURE 4
Lamprey Databus Flow Path

The following paragraphs will further explain how a Lamprey type system would work and incorporate the basic design requirements for a mobile, high fidelity trainer.

The Lamprey system would be highly mobile and be able to be deployed anywhere. The entire system could be made capable of running off the same portable "yellow gear" power carts that power the aircraft. Note that the aircraft itself would have to be electrically powered for this method to work. The portable training system

would then reduce to a compact wheel-mounted system that could be moved from aircraft to aircraft as the situation warranted.

If the aircraft was initially designed with loop holes for Lamprey systems in the future then most of the aircraft systems could be turned off during training. Most if not all the special situations described above could be taken care in the mission computer software load. With such a design, once the Lamprey system is attached to the aircraft the mission load would recognize a training session and override normal aircraft responses. Once the Lamprey is disconnected, the aircraft would respond in the normal matter. This design concept would remove the chance of mistakes that would produce a mishap.

Since the aircrew will be using an actual flight asset for training the cockpit will not have to be modified to increase the fidelity. The technologies for man/machine interfaces in aircraft are pushing for "glass" cockpits and control of systems through a data-bus will keep a Lamprey system from having a large integration factor when the trainer is to be used. Until modern cockpits are fully integrated onto a data-bus, Lamprey will need to interface to these instruments. If these instruments are critical for training, flat-panel LCD display devices could be clipped into place over the existing non-functional displays, or the faces of the dials could be programmed into the helmet-mounted visual system to update as required. The system would appear as illustrated:

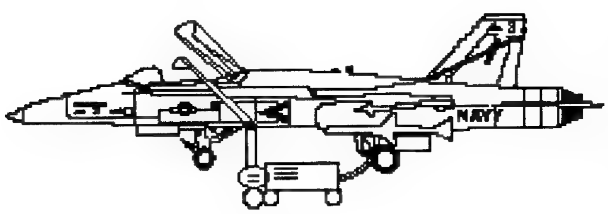

FIGURE 5
Lamprey System Concept

The visual system for the illusion of movement could be presented to the pilot with a boom-supported helmet mounted display system. This could to be attached to the box that housed the host computers and 1553 bus interfaces. There will most likely be display helmet sensor positioning and interference issues with the aircraft's canopy, but these should be workable.

A Lamprey system would be able to reuse the software models written for the OFTs/WSTs. There would be little change to the aerodynamic models. The avionics software models would be incorporated so that the actual expensive hardware on the aircraft would not have to be used. The power to the aircraft would only be used to drive cockpit displays, control positions and the data-bus to the Lamprey system.

Configuration changes to the trainer would be a very simple task. Since the trainer incorporates a helmet mounted display and the trainer is bought to the cockpit, to change the configuration all that will have to be done is to run different aerodynamic, avionics and aircraft interface software models.

The whole Lamprey system could be COTS supplied. The power for the system could come from the same source that is generating power for the aircraft systems.

The Lamprey concept could be incorporated in future designs of aircraft to handle the data flow and integration more cleanly. If the basic designs of aircraft incorporate "loop holes" in mission computer loads and aircraft data-bus integration ports, the Lamprey system would have a cleaner interface design and not be considered as an after market add-on. Full testing of the aircraft and trainer union could be accomplished to reduce the chance of mishap.

Benefits of Lamprey System

There are five major potential benefits of a Lamprey system. First, and most obvious, the use of an actual tactical asset negates the need to build a high fidelity and often expensive simulation system. First, the system does not require a unique piece of training gear, which also removes the need for an entire infrastructure system for support personnel, spares, training of the support personnel, etc. To fulfill the need to maintain the trainer the existing aviation support personnel could be cross-trained on how to remove defective components from the boxy training device and return them to a depot for repair.

Second, In practical terms, there is usually one aircraft per squadron or airwing that is "down" for extended repairs, the infamous "Hangar Queens" or even a series of aircraft that are in a

non-flying status for a variety of reasons. If the malfunction or failure of the aircraft was not serious enough to affect the cockpit control systems, an aircraft laid up for repair could be used for the Lamprey device, making lemonade out of lemons. This would turn a downed asset into the trainer of the week.

Third, and perhaps as important as any other function, the Lamprey could be used to help repair crews isolate a malfunction, and reproduce malfunctions seen in flight on the ground. The Lamprey could be set to run a series of canned maneuvers "through" the aircraft, or even replay a recorded series of actual flight evaluations, to help reproduce and/or isolate the problem with the aircraft. As a last method for fault isolation, the pilot who reported the problem could fly the system to the point where the problem occurred. This capability would, of course, be limited to debugging electrical systems and hardware only.

Fourth, a device such as the one being outlined would be a very cost effective way to profile missions in a squadron or group setting. The major push for the next generation training system will be to accomplish mission planning and rehearsal. If enough devices exist, groups of aircraft could practice maneuvers using the net-workable nature of the device and include the latest information on the target's position and capabilities. The addition of a photo-textured mission rehearsal visual system (with the incurring of some large additional cost) would add the ability to perform actual strike package rehearsals using the actual aircrew and aircraft that will fly the mission.

Finally, a Lamprey type system would be sizable to the mission desired. A pure cockpit procedure's trainer need not even have a visual system, and this represents the lower end of the systems possibilities. Visual image generators could then be provided as required, up to the mission rehearsal type devices mentioned above.

Drawbacks of the Lamprey

There are drawbacks to this type of design, and some are potential "show stoppers."

One of the basic laws of any Lamprey type system should be: *The flight asset cannot be modified in any way.* This would preclude any unfortunate events that might occur. As an example, perhaps, to save wear and tear on the airframe's actuators we insert a modification to the aircraft that causes the control surfaces not to respond when the pilot moves the control stick in the aircraft when the Lamprey is attached. Obviously, leaving this training modification in, or inadvertently turning it on in flight would have disastrous consequences.

Another problem is that there are some systems that could simply not be allowed to operate in their normal manner without mission and fight control computer loads changes. Using examples again, it would be unfortunate if a pilot training in take-off succeeded in raising his gear or a comrade succeeded in dropping a bomb training for a strike package while sitting in the hangar space of a carrier. The host computer would have to recognize the command on the bus "raise gear" and over-ride the actual aircraft systems response, not allow the gear to transition, and then display to the pilot that in his virtual world the gear had moved.

Finally, while such a system could be easily integrated into an aircraft that is data-bus driven and fly-by-wire, the system becomes harder and harder to integrate into an aircraft that does not use such systems for display of information. A good example would be a 1960's designed AH-1W attach helicopter, which uses data-bus information only for a Heads-Up Display, with all the other displays being driven electro-mechanically. For a system such as this, most of the aircraft's interior would have to appear as virtual reality systems in the image generator, which would drive costs up sharply.

Costs from both type systems should range from \$5 -- \$20 million per copy. The operational cost of the Lamprey system is estimated at \$400.00/hr. The costs break down to \$200.00/hr. Escrow for repairs to aircraft hardware, \$50.00/hr. for the pilot, and maintenance personnel, and \$100.00/hr for electrical power.

SYSTEM USAGE EXAMPLE: MISSION REHEARSAL

In the field the concept could be used as follows. A deployed force of mixed aircraft type has three Lamprey type systems for fixed wing aircraft, and three SMTs for rotary wing aircraft. This scenario assumes the usage of a photo-visual, rapid turn-around visual system and a mission requiring a mix of aircraft types.

Days, weeks or even hours before the mission, reconnaissance assets over fly the area leading to the objective. The results are incorporated into the visual systems for the SMTs and the Lamprey type devices. Planning begins at once. Using three squadron aircraft, the Lamprey systems are attached, and the flight leaders use the system, along with all the usual materials available to them, to plan and profile the mission. The flight leaders of the rotary wing aircraft are performing similar functions.

Once the mission is planned, flight leaders begin leading their teams through the mission, linked and interacting only with similar aircraft types.

Finally, the entire mission group trains together, will all participants planning and training in rotation through the mission until all pilots involved have practiced in a linked, interactive environment. Simple workstations allow command and control forces to interact with the group in real-time.

The result is a mission group that has flown the mission many times in a virtual world before the actual mission is undertaken. Command and control procedures have been rehearsed, as have problem scenarios and tactics. Of course, no such scenario can anticipate totally the response of the other side, but such a training session could even be linked with the best aggressor doctrine and tactics models to produce a training environment that may be capable of closely anticipating reality.

COSTS AND BENEFITS

On the positive side, SMTs offer mobility, excellent training value, low cost, on-site availability and a mission rehearsal capability. Drawbacks include a lack of motion cueing systems, space requirements onboard ship, and the burden of additional support requirements for squadrons.

Lamprey type systems have as benefits the following: re-use of expensive tactical assets, on-site availability, maintenance usage and superior realism and fidelity. Drawbacks include the following: Use of an expensive tactical asset, lack of motion cueing, and the technical complexity required for the visual image generation system.

Both systems share the advantage of being able to make use of today's advanced visual systems and networking capability for mission rehearsals over the actual tactical area with the actual flight crews required, including, if desired, command and control groups.

SUMMARY

The technology exists today to produce a new type of high fidelity trainer. All the components of the systems discussed in this paper exist and are off-the-shelf available. These trainers can either be independent, mobile systems that move to the point of greatest need, or be "strap-on" systems that attach to actual tactical assets. Usable in the field, on networks, and with mission rehearsal visual systems, such systems can supplant or replace existing systems in usage for low cost and with short development times required. Small mobile trainers and strap-on training systems can meet the needs of today's military both in the field and in the area of fiscal reality.

BIOGRAPHY

Mr. Miller is the team leader for the tactical aircraft simulation section of the MFS facility, a section that encompasses the Navy's F/A-18, F/A-18E/F, AH-1W and EA-6B simulation efforts. He received his B.S. degree in Aerospace Engineering from North Carolina State University of Raleigh, North Carolina, U.S.A. in 1986. Mr. Miller has been a member of the AIAA since 1984.

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Mr. Davis is a lead avionics engineer for the Aircraft Simulation Division of the Manned Flight Simulation Facility. He has been involved in the development of the AH-1W APT and the V-22 GTPT simulations. He received his B.S. degree in Computer Science from Frostburg State University in 1988, and his M.S. degree from Florida Institute of Technology in Management in 1990.

SIMULATION, DISTRIBUTED SIMULATION, and SYNTHETIC ENVIRONMENTS

Future Applications and Challenges

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SUMMARY
This survey paper reviews current practices in simulation technology with emphasis on aircraft development and testing, followed by a discussion of present and future applications of distributed simulation and synthetic environments. The aviation community has used a wide variety of simulation tools for over 35 years. The benefits of current generation standalone simulation tools, including system integration laboratories, are well understood. Distributed simulation is beginning to be used to support training and requirements definition; test applications are also beginning to be explored. Advanced distributed simulation provides an unprecedented opportunity to explore new concepts as well as improve the efficiency of test and training activities.With the rapid increases in information processing technology, synthetic environments will be used increasingly to support test and training, both in standalone and interactive distributed modes. There are numerous challenges in developing and applying these technologies; including simulation fidelity and scalability, verification and validation. There is also a need to decrease simulation costs. The emergence of distributed simulation has been the catalyst for increased interaction between the simulation world and test and training systems. Next generation range and platform instrumentation architectures will be designed to facilitate interaction between live players and simulated entities.

INTRODUCTION
Good afternoon ladies and gentlemen. It is a pleasure to be here with you today. Over the past several days speakers have reviewed the state of the art in flight simulation and simulations used for engineering and training. The concluding session of this symposium properly addresses the broader issue of Future Applications of Simulation Technology.

One of the objectives of this survey paper is to help the Flight Vehicle Panel develop your Aerospace 2020 concept paper. In this paper, we briefly review current practices in simulation technology with emphasis on development and testing, then address the use of distributed simulation and synthetic environments to support the requirements, development and training processes. We address these issues in a broad context including, but certainly not limited to, aircraft development.

This is a dynamic time for both government and industry. In the past few years, we have seen the Warsaw Pact and the Soviet Union disintegrate. These events have properly triggered a significant decrease in defense spending, but most people recognize that there is a need to continue to maintain an effective military capability against a range of regional threats. In addition, military forces are being called upon to perform a spectrum of non-traditional roles, including humanitarian support activities, evacuation operations, disaster relief, peace keeping, counter-terrorism and counter proliferation support. These new roles, when combined with a wide variety of potential regional threat scenarios, makes the tasks of requirements definition, testing, training, tactics and doctrine development far more challenging than in the past. Simulation technology can be a powerful tool in meeting these challenges. This paper surveys the status of these tools and addresses future applications with emphasis on advanced distributed simulation (ADS).

USE OF SIMULATION FOR AIRCRAFT DEVELOPMENT, TEST
The aviation community has used a variety of simulation tools extensively in support of system development and test and evaluation for at least 35 years. Simulations and physics-based models are

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used at the subsystem level, in standalone, engineering-level simulations as well as for mission-level assessments. Fixed-based and motion simulators are key instruments in flight control system development. This Flight Vehicle Panel symposium reviewed the state-of-the-art in flight simulation, visual and motion cueing, as well as advances in simulation for aircraft design and development. One topic not previously addressed during this symposium is the increasing use of system integration laboratories in support of aircraft development. These facilities, which are defacto complex hybrid simulation systems, include actual aircraft subsystem hardware, subsystem models, and system stimulators. A system integration laboratory, located at the airframe manufacturer's facility, has become an integral part of the development of each new aircraft model. Integration laboratories are sometimes located at the avionics integration contractor's facility as well. Earlier generations of avionics consisted of a number of federated subsystems, some of which were pod-mounted. The F-22 design is the first production application of an integrated avionics suite on a new aircraft. With this generation aircraft, integration laboratories are becoming increasingly important in the development of extensive and complex interfaces, distributed on-board as well as off-board, including aircraft-aircraft links, ground and satellite links.

There is another set of generic simulation-intensive aircraft system development and test facilities which have evolved to support the development of aircraft electronic warfare systems, weapons sensors and guidance systems. Some of the major facilities are listed below.

- Air Combat Environment T&E Facility (NAWC, Patuxent River, MD)
- Electronic Combat Integrated Test Facility (Edwards AFB, CA)
- Guided Weapons Evaluation Facility (Eglin AFB, FL)
- Theater C2 Simulation Facility (Kirtland AFB, NM)
- AF Electronic Warfare Evaluation Simulator Activity (Ft Worth, TX)
- Real-Time Digitally Controlled Analyzer Processor Activity (Buffalo, NY)

The Air Combat Environment Test and Evaluation Facility (ACETEF) is the most versatile and advanced electronic combat integrated test facility. It features an anechoic chamber large enough to accommodate a fighter aircraft, an electromagnetic warfare integrated systems test laboratory, an electromagnetic environment generation system, and a manned flight simulation facility. The ACETEF has been linked to most of the other facilities listed above, as well as a variety of other simulation facilities throughout the U.S. It is rapidly becoming a node in a variety of distributed exercise and training simulations, as well as a system development and test facility.

It should be noted that the above facilities were all originally developed to operate solely in a stand-alone mode. With the advent of distributed simulation, most of these facilities are now being netted to operate in a mode not envisioned earlier; in a linked mode as well as stand-alone. They are becoming nodes in a number of on-going and planned distributed simulation activities, which are discussed later.

Based on years of experience, the benefits of using system integration laboratories and hardware in-the-loop simulators for development and testing are well understood and accepted. The majority of the subsystem integration and checkout tasks can be accomplished in a system integration laboratory. When compared to flight testing, the process is far more efficient, the experiment is controlled and test execution is rapid, relatively simple and inexpensive. The inefficient fly-fix-fly approach is minimized. Simulation has also long been used in direct support of flight testing in the following ways:

- Pre-test analysis, scenario development
- Test planning
- Crew test procedure rehearsal
- Post-test evaluation
- Anomaly investigation

SIMULATION CATEGORY DEFINITIONS

With this background, we will transition to emerging developments in distributed simulation. Some definitions and concepts are useful aids to the discussion. First, a 1992 U.S. Defense Science Board Study on "Simulation, Readiness and Prototyping" defined categories of simulation as follows:

- Live: Operations with real equipment in the field
- Virtual: Systems and troops in simulators fighting on synthetic battlefields

- Constructive: Wargames, models, analytical tools

The Defense Science Board observed in the study that everything is simulation except combat. This is a more global view of simulation than the more widely held construct which makes a distinction between actual hardware and a system which is replicated in some fashion. This broader construct has implications for system development and test. We will discuss these implications in view of emerging simulation technologies; in particular advanced distributed simulation and improved synthetic environments.

ADVANCED DISTRIBUTED SIMULATION OVERVIEW

Advanced Distributed Simulation (ADS) may be defined as the set of technologies used for creating realistic synthetic environments that can be entered from worldwide locations in real time. Advanced Distributed Simulation (ADS) is not a single thing or model that can be rigorously specified and built, but rather a suite of constantly improving tools and techniques for assembling dynamic and disparate federations of models and simulations as well as real platforms and real systems of all types and sizes that interoperate together. Interoperation is the single most critical feature of ADS and represents a dramatic departure from earlier generations of models and simulations that were incapable of working together, indeed were never thought of as needing to work together.

The fundamental change in the last ten years is the realization that modern models and simulations are based on the same underlying information technologies and can and should be designed to be connectable as a guarantee of interoperability and compatibility. This change will result in a more generic approach to modeling and clearer responsibility for ownership of system/weapon characteristics and effects (the algorithms). This is a more cost effective approach for customers since fewer redundant (and conflicting) simulations should result. This will , in turn, alleviate current verification, validation and accreditation problems. There has been increasingly widespread recognition of this change, especially by the DoD Defense Science Board and the science and advisory boards of the military Services.

ADS offers the potential for fundamentally new capabilities:

...The creation of very large, complex battlefields...

...that can be entered efficiently from remote locations (no need to travel to a gaming center or exercise range)...

...by large numbers of warfighters...

...at a high degree of granularity and fidelity if required...

...for a variety of applications and purposes (training; mission planning; dress rehearsal operations, command, control; after mission review; concept development; requirements definition, simulation based design; engineering development test and evaluation; force structuring; tactics & doctrine development; etc.)...

...where commanders can use operational communications and operational systems (actual command, control, intelligence systems)...

...outcomes can be visualized, inspected, analyzed, and understood better than before

...and results can be communicated to senior military and political decision makers using more effective and vivid visualization techniques which characterize performance effectiveness and limitations.

ADS is based upon distributed computing structures, so the key enabling technologies include the rapidly increasing power of workstations, microprocessors, data bases, software tools, and emerging nationwide and worldwide digital networks that tie all of these together. With their new processing power it is possible to support the requisite realism in graphic rendering and visualization of the simulated environment to interact effectively with a human in real time. ADS has also been a catalyst for good information technology practices such as common data dictionaries and open architecture.

With that overview, we will review several charts which illustrate the concept. *Figure 1* illustrates a diverse set of players interacting on a distributed network which provides the battlespace environment. The players broadcast and receive state data from the network. *Figure 2* (AWACS example) illustrates the ability to mix and match real and virtual players in an ADS environment. The virtual players could either be created on-board the AWACS, or uplinked from the ground from a virtual AWACS. In a beyond visual range environment, virtual players can be injected seamlessly. To illustrate the flexibility the concept provides, assume that a training mission is scheduled and the AWACS has to cancel or abort for some reason. Segments of the mission could still be performed from the ground-based virtual

AWACS, which could be patched into the exercise initially in a parallel passive monitoring mode. The implementation of this concept requires that ground based systems be built to the same architectural standards and have functional compatibility with the airborne system and associated simulators.

Figure 3 illustrates the options associated with the use of sensitive or classified models. Assume the task is to evaluate an aircraft with low observable characteristics against a potential threat acquisition or tracking radar. For a mission planning system, one would need access to detailed models of the aircraft as well as the potential threat radars (top illustration). However, if the aircraft were one of several types used in an exercise for which access to the specific aircraft characteristics was not allowed, the simulation would only provide bi-modal detect/non-detect information based on the aircraft's attitude and bearing from the radar. This information could be altered further as appropriate to provide protection against revealing actual detection ranges.

With that brief overview of the advanced distribution simulation concept and a look at some sample applications, it is worthwhile to make some assumptions. First, it is assumed that next generation military leaders will be increasingly comfortable with and supportive of simulation technologies. Second, military commanders will be receptive to "productized" ADS that they can use "on their watch" to solve current problems. Third, next generation test and training instrumentation will be ADS compatible. On-board interactive embedded training subsystems will be incorporated during production of next generation aircraft, ground vehicles, and ships. The initial focus of ADS will be on training and tactics involving large numbers of players. Emphasis will be placed on: visual environment; human in-the-loop activity (generating requirement for near-real-time); and keeping bandwidth down to accommodate many players.

Synthetic environments[1] will be used increasingly to support test and training, both in standalone and interactive distributed modes. Simulation offers the potential to provide representative test environments that cannot be created physically for field tests for a variety of reasons including cost, safety, availability, logistics, and environmental conditions. Applications include:

- Adding assets
    - Friend, threat, unidentified
    - Two-way interface between virtual and live forces beyond visual range
- Expanding scope, events, trials
- Near real-time endgame analysis
  Leveraging human factor/live response testing
- Improving environmental robustness
    - Natural
        - Weather, diurnal effects, obscuration
    - Man made
        - EW, EMI, target signatures (IR, UV, noise, etc.), obscuration
    - Terrain
        - Topography, cultural features
        - Manmade features
        - Terrain changes: military action, weather

Within the next decade, advanced distributed simulation will have relatively few applications to system development and testing when compared with training applications. However, many of the same simulations will be used in a standalone mode for test support. The focus during system development and test is properly in the actual hardware/software being developed. The requirement to connect geographically dispersed elements in near real-time to support development is limited. As has been previously mentioned, a wide variety of simulation and system integration laboratory tools are used to support development. The majority of these tools are interactive, but are not normally distributed.

The following list contrasts some of the differences in simulation requirements between test and training.

- Testing may not require many players
- Test accuracy may require larger bandwidths
- Testing requires high fidelity physics-based models of individual entities
- Test data rates are generally higher
- Some test applications do not need human-in-loop interaction

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[1] Some members of the simulation community restrict the term synthetic environments to natural physical environments such as weather and topography. It is used in a broader sense in this paper to encompass any element that is modeled or simulated.

- Near real-time may or may not be a test requirement
- Architectures and data structures may have to be test/event specific
- Testing is "scripted" vs training "free play"

The emergence of advanced distributed simulation is the catalyst for increased interaction between the simulation world, test and training. This has major implications for next generation range instrumentation and simulation systems as well. Range and platform instrumentation architectures will be designed to facilitate live player and simulation interaction. There will be increased commonality between mission control displays (test and training) and simulation displays. Data from live players will be merged with simulated friendlies and threats. This has command/control implications, which will be addressed later. Post-mission display /debrief systems will be used to support simulation verification and accreditation activities, as well as their normal functions.

Figure 4 (Simulation Applications) summarizes the relative utility of stand-alone and distributed simulations to support system requirements definitions, developmental and operational testing, training and tactics and doctrine development. This chart is constructed to compare the scope of applicability of standalone and distributed simulation tools. "Low" is meant to convey a relatively limited number of applications rather than a value judgment about the applications for which it is used.

ADVANCED DISTRIBUTED SIMULATION CHALLENGES

There are a number of challenges in developing and applying advanced distributed simulation. Technical challenges associated with test applications include:

- Scalability
- Fidelity
  - Higher resolution entities
  - Integration of live, virtual and constructive entities
  - Threat emulation using distributed signature models
  - Terrain/environment representation
- Data rates, latency, update rates
- RF data links for virtual threat injection
- Verification, validation, accreditation
- Lower cost
- Cultural: Acceptance by test community

There are some special challenges relating to the use of ADS in support of operational testing. In general, the operational test community is more suspicious of models and simulations than are material developers, developmental testers, and trainers. However, as resource, safety and other constraints become more restrictive, the operational test community will be forced to make more use of simulation tools. As an example, the number of live missile shots required to achieve a high level of statistical confidence may not be affordable. As a result, simulations will be increasingly used in conjunction with actual test results. Operational test information will be one data source to independently verify, validate and accredit (VV&A) the simulation. The operational test community may also be reluctant to use ADS tools, primarily because of the additional VV&A burden associated with the elements of a distributed simulation not under their control.

There are several command and control challenges that must be addressed if the objective is "seamless" integration of live and virtual players. There will be a range safety requirement for positive differentiation between real players and virtual entities for range safety, air/ground traffic control and search and rescue purposes. Rules of engagement will require attention. This is a potential constraint on system architecture, which will dictate at least three data paths; one for range safety command/control and one for individual "players," and one "player" command/control which will be further subdivided into friendly and adversary command/control.

Threat representation challenges include the need to simulate numerous potential regional threats in a wide variety of threat scenarios. Because of the potential for numerous combinations of red, gray, blue threat arrays, it is impractical/impossible to test/train across the threat spectrum. Synthetic environments provide an opportunity to alleviate this constraint.

Finally, the variety and scale of joint task force scenarios in a NATO environment make it impractical to consider staging large exercises as the principal means of evaluating new systems or tactics. By using ADS, synthetic environments and scenarios can be created to evaluate the effectiveness of a new system, doctrine, or potential threat scenario.

KEY ACTIVITIES/DEVELOPMENTS

Next we will give a brief overview of several key activities and developments that are underway in the U.S. which involve advanced distributed simulation and synthetic environments. This overview will provide some insight into the diversity of applications of these emerging technologies.

- Synthetic Theater of War
- Joint Tactical Combat Training System
- Joint Advanced Distributed Simulation Test and Evaluation
- Ship Self Defense Synthetic Test Range
- Joint Precision Strike Demonstration

Each one of these activities could be the subject of a detailed discussion. Our purpose here is only to briefly summarize the activity to provide some insight into the breadth of developments relating to advanced distributed simulation.

The purpose of the Synthetic Theater of War (STOW) is to provide the ability to construct a variety of synthetic environments to perform several functions including training and readiness, doctrine development, requirements definition, and equipment design and prototyping. These functions will be performed primarily with virtual simulations with the option of integrating live forces and constructive simulations. The STOW goal is to develop a suite of simulation technologies including behaviorally accurate computer generated forces, high resolution environmental representations, and distributed networking technologies.

The objective of the Joint Tactical Combat Training System (JTCTS) is to provide an at-sea combat training capability for an expeditionary force and a land-based capability for air crew training. It will include both a fixed capability which will be used to reinstrument existing air combat training ranges and a mobile capability. One of the objectives of the JTCTS program is to provide realistic threat representation via data links to uplink air defense and other threat information. The cost of maintaining and operating large aggressor aircraft units and ground-based air defense threats is becoming prohibitive for training purposes. This will be the first large scale training application of distributed simulation technology and will include stimulation of on-board platform sensors.

The objective of the Joint Advanced Distributed Simulation Joint Test and Evaluation is to investigate the utility of Advanced Distributed Simulation for both developmental and operational testing. Two major test activities are currently planned: a systems integration test involving an advanced missile system; and end-to-end theater battle arena systems test. The objective of the test activities is to evaluate ADS technology, rather than test the systems involved in the experiments.

The objective of the Ship Self Defense Synthetic Test Range is to develop a synthetic environment where the ship self defense problem can be assessed in a manner that preserves tactical and technical details. The demonstration will include both real systems and models. The goal is to examine system performance and operation in a variety of high fidelity scenarios.

The goal of the Joint Precision Strike Demonstration program is to introduce and implement new technologies into the defense arena that address the precision strike mission. A live-simulated virtual environment is being used to evaluate technologies, train users, and perform experiments necessary to reduce sensor-to-shooter timelines and to attack high-value, time-sensitive targets. Whenever possible, JPSD uses the actual hardware to conduct these demonstrations.

CONCLUSIONS

The next decade will be exciting and challenging as the NATO defense community continues to adjust to profound political and budget changes. There are potentially new adversaries, less formidable but also less well defined. Simulation technology will play an increasingly important role in requirements definition, testing, training and tactics, and doctrine development. Advanced distributed simulation provides an unprecedented opportunity to explore new concepts, command and control systems, and for joint development of tactics among the NATO member nations. Experimentation is needed to mature the technology and fully explore the concepts. The challenge is to be innovative in taking advantage of the powerful simulation tools that are becoming available.

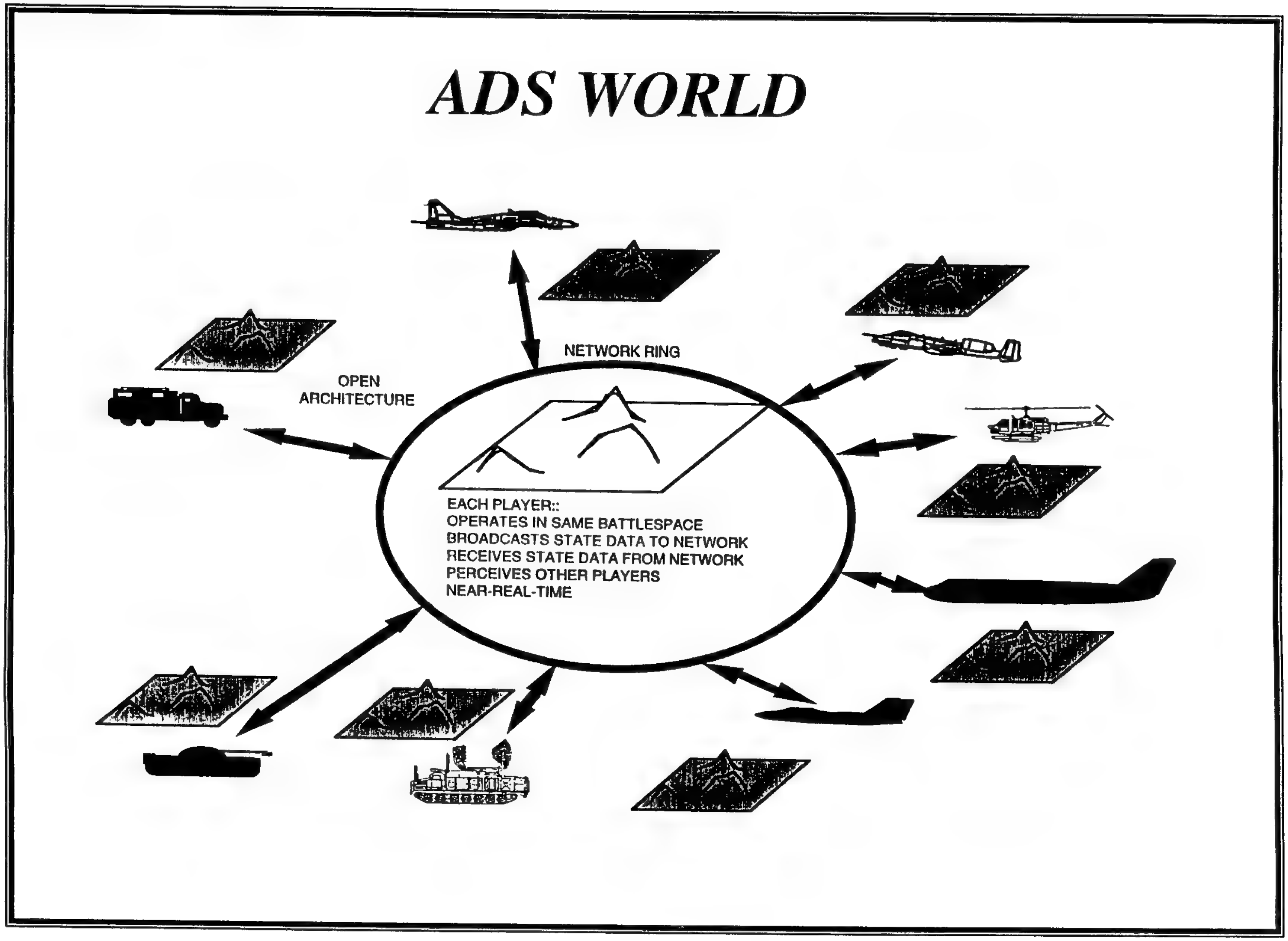
ADS WORLD
NETWORK RING
OPEN
ARCHITECTURE
EACH PLAYER::
OPERATES IN SAME BATTLESPACE
BROADCASTS STATE DATA TO NETWORK
RECEIVES STATE DATA FROM NETWORK
PERCEIVES OTHER PLAYERS
NEAR-REAL-TIME

FIGURE 1

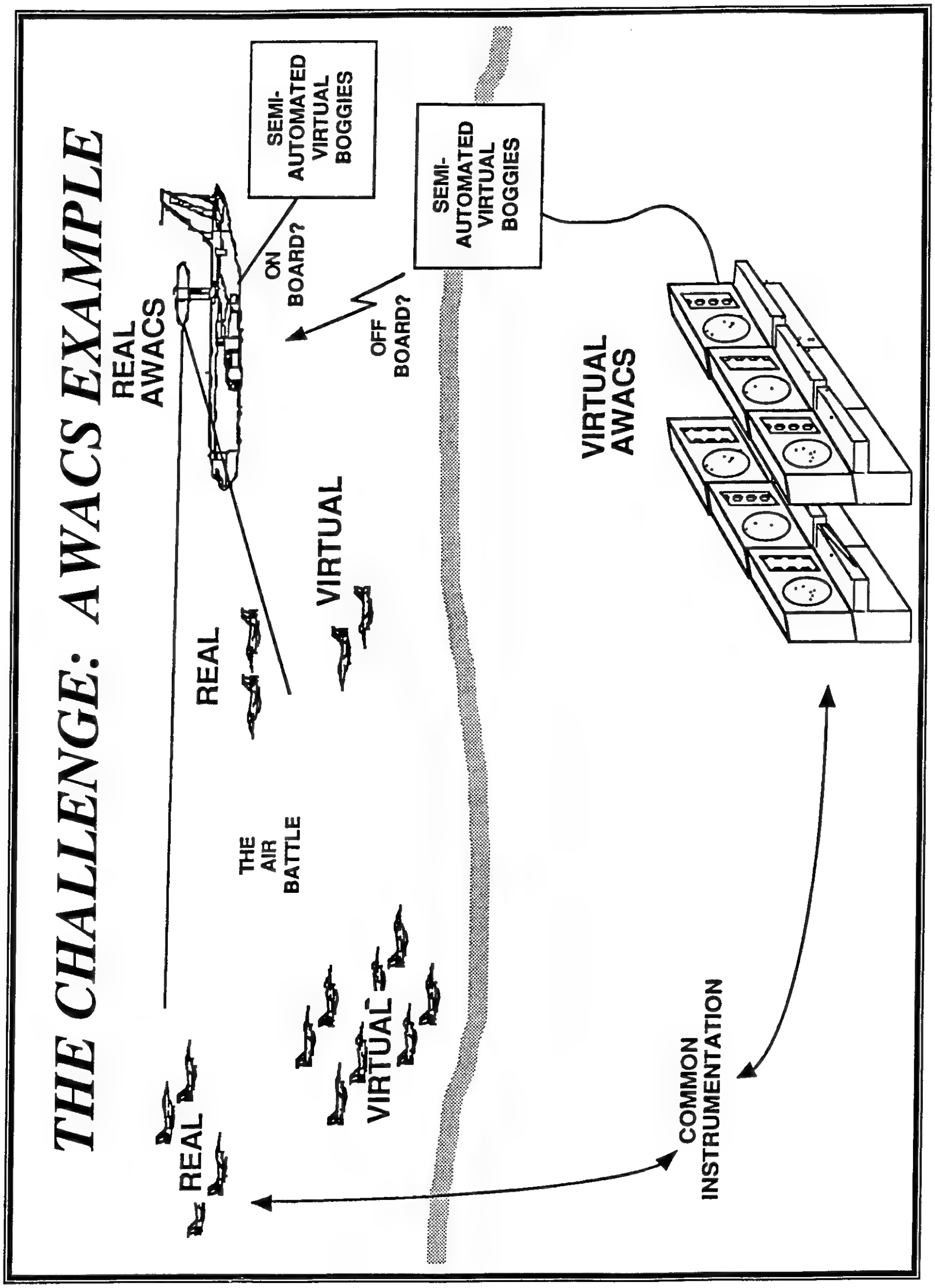
THE CHALLENGE: AWACS EXAMPLE
REAL AWACS
SEMI-AUTOMATED VIRTUAL BOGGIES
ON BOARD?
OFF BOARD?
SEMI-AUTOMATED VIRTUAL BOGGIES
VIRTUAL AWACS
REAL
VIRTUAL
THE AIR BATTLE
REAL
VIRTUAL
VIRTUAL
COMMON INSTRUMENTATION

FIGURE 2

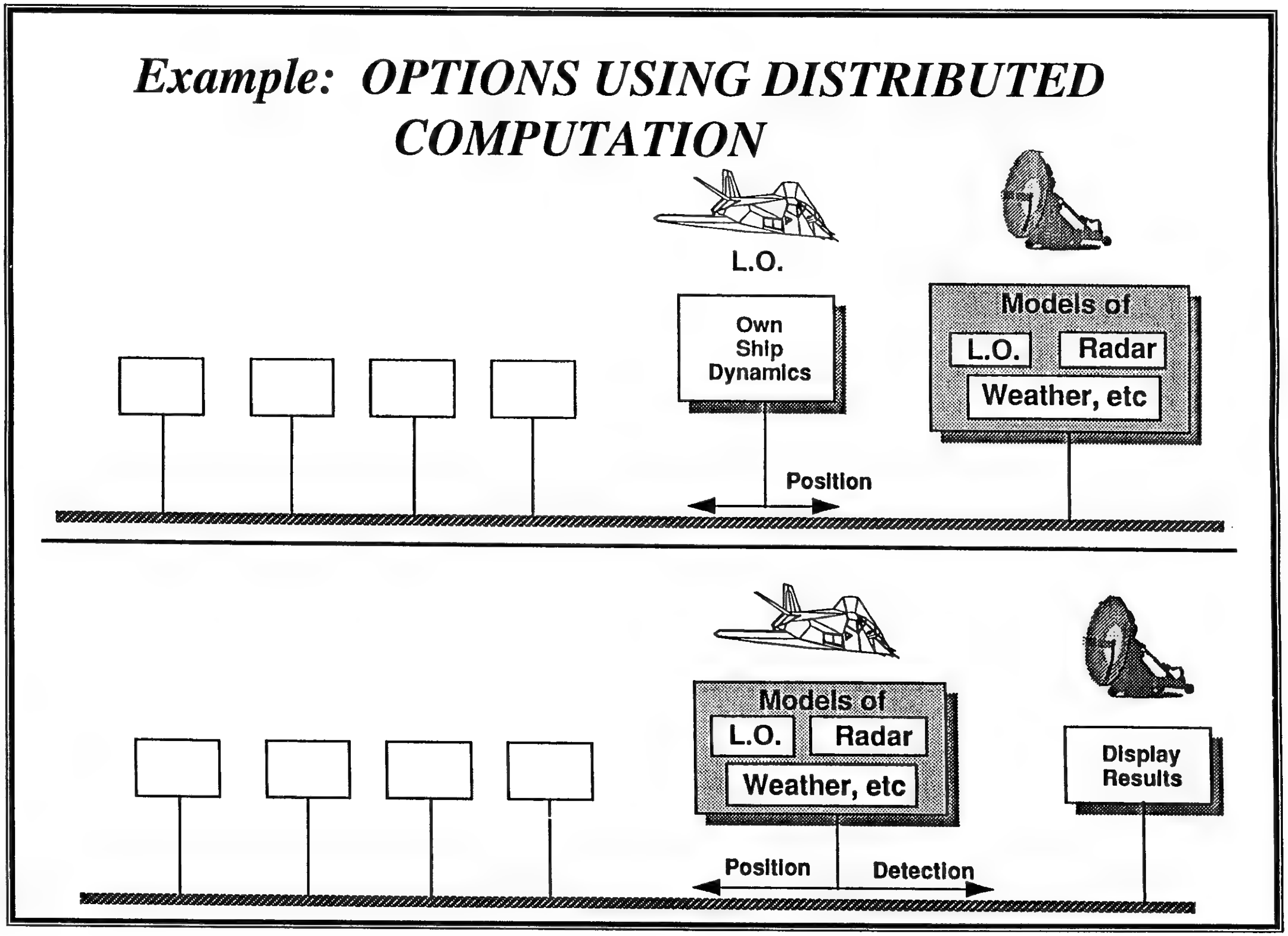
Example: OPTIONS USING DISTRIBUTED COMPUTATION
L.O.
Own Ship Dynamics
Models of
L.O.
Radar
Weather, etc
Position
Models of
L.O.
Radar
Weather, etc
Display Results
Position
Detection

FIGURE 3

SIMULATION APPLICATIONS

	STAND-ALONE		DISTRIBUTED
	HIGH FIDELITY	MEDIUM FIDELITY	(ADS)
SYSTEM REQUIREMENTS DEFINITION	H	M	L
DEVELOPMENTAL TESTING	H	L	L
OPERATIONAL TESTING	M	L	L - M
TRAINING	M	H	M - H
TACTICS & DOCTRINE DEVELOPMENT	L	H	M

H = High, M = Medium, L = Low

FIGURE 4

THE SYNTHETIC ENVIRONMENT - THE ULTIMATE DEFENCE SIMULATION?

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SUMMARY

References to 'Defence Synthetic Environments' are becoming more common with the passage of time. At present, the term means different things to different people driven largely by their viewpoint within the defence business. Indeed, to confine the concept to the defence business is already narrowing the vision according to some. There are envisaged opportunities for applying similar techniques in commerce, medicine, transport and so on. In fact any large system is a potential candidate.

The defence business was, however, probably the first to adopt the name and to start demonstrating what it means. In the UK, joint government and industry groups have been established to steer national activities for SE's. A number of early demonstrators are underway. In the USA, regular networking demonstrations illustrate how this particular component of SE is maturing. The general impression is one of commitment to SE as a long term goal.

The intention of this paper is to give a view of the extent of Synthetic Environments (SE) and to discuss how it may be put together and used to help the defence business. In doing this the role of Flight Simulation within SE is highlighted along with the challenges which it faces.

The need for improvements throughout the defence business hardly needs justification here. Pressures created by falling defence budgets, uncertain threats, shorter development times and heavy competition all point to the need for process improvements right across the board. To embrace the opportunities offered by SE requires changes in all the parties involved including the customer. The resulting increase in effectiveness and level of concurrency between all the stakeholders should be a worthwhile payback.

DEFINITION OF DEFENCE SYNTHETIC ENVIRONMENT

Currently there are a number of variants on the definition, primarily because of the different viewpoints held by those defining it. In principle, though, they are similar.

For the purposes of this paper, the following definition is proposed.

A computing based environment which allows the risk reduction of defence issues to take place through the interaction of people, models and live equipment in order to:

- ☐ Assess the impact of Force Structure changes
- ☐ Assess alternative methods of warfare
- ☐ Develop doctrine, tactics and mission plans
- ☐ Rehearse joint missions
- ☐ Train force commanders and personnel
- ☐ Develop and assess products, needs and concepts
- ☐ Allow concurrency between customer, user and provider

The human content of the SE is viewed as one of the essential ingredients. There are a number of ways in which the human interacts with the SE including training for military decision making, training for weapon system operation or investigating doctrinal options. In other parts of the SE, the human is making product design decisions. Throughout the SE the common theme of human interaction with computers, real equipment and other people occurs.

Clearly, a tool which can meet all the above defined requirements has vast scope. Each user of the SE would actually use subsets for his own purposes whether they be training, requirement capture or whatever. Because subsets of a shared environment rather than independent sets would be used, as is the tendency to date, a consistency occurs which widens the scope of computer modelling that can be undertaken. The new levels of integrity produced by the SE modelling process will significantly increase the value of the results produced.

Simulation and modelling is already widely used within the defence business in many of the areas covered by the above definition. Currently the techniques are well developed in certain areas but far less so in others. It is also carried out in a fragmented rather than an integrated way. SE can be seen as the 'umbrella' which hosts this integration.

OVERVIEW OF SE HIERARCHY

A way of visualising the hierarchy of processes to meet all the defined requirements is shown in Fig 1. These layers serve different purposes and in many cases have different users. They are arranged in this way to emphasise the 'vertical integration' or consistency between them which allows data representing weapon systems to move freely between layers.

The upper levels of the SE tend to relate to user requirements derived from defence commitments. This is where customer defined geopolitical scenarios would be input to the SE.

The strategic models are the highest level of wargaming - probably at the campaign level. The next layer provides

Paper presented at the AGARD FVP Symposium on "Flight Simulation — Where are the Challenges?", held in Braunschweig, Germany, from 22-25 May 1995, and published in CP-577.

indicative costs for such a strategy and identifies the logistic support implications.

Moving down through the hierarchy, the models become more specific weapon system simulations either as aggregated forces or individual platforms. At this central level there are a number of uses for the SE including requirements capture, performance evaluation and personnel training.

As the lower levels are reached, the solutions to requirements are being produced. These can feed back to higher levels so that vital cost/performance trade-offs can be done. Flexibility of movement through the levels is the key to the benefits of the SE.

THE SE USERS

In order to illustrate something of the degree of integration which is required for SE, it is appropriate to consider the different types of user and how they interact with the SE processes.

SE for Forces Training and Mission Rehearsal

The core of this SE subset is shown in fig 2. The task is to use the models and equipment within the SE to improve the performance of personnel. This can take place at the operator level where skills in using particular equipment are to be acquired or at commander level where the training is aimed at decision making.

The process assumes mission plans, doctrine and the current definition of training procedures. The real-time simulations and wargames are used by personnel and commanders to improve their various skills. During the process, measures of operator training effectiveness and mission effectiveness are produced and analysed. Shortfalls in training effectiveness are corrected by changes to training procedures.

Using the SE for Mission Rehearsal is a special case of its use for Training. The emphasis rather than on skills acquisition is instead placed on familiarisation with a particular pre-defined scenario and tactics which have been produced by a separate Mission Planning activity (see next section).

In order to produce a realistic training task for operational training or mission rehearsal, it may be necessary to network the realtime models or equipment into large scenarios both to increase the realism and/or to allow simultaneous training.

Large networks of geographically separate simulators are often referred to as SE's. However, simulator networking is just one of the many enabling technologies which are used within the SE.

The linking process between wargames and simulators is an example of vertical integration. Ref 1 discusses the principles of vertical integration.

SE for Mission Planning

It is unlikely that the 'what ifs' to be tried in order for mission plans to be refined would be carried out with individual simulated entities such as manned simulators. More likely these trials would use the established wargame techniques based on aggregated entities and computer generated entities such as aircraft. It is probably inappropriate to include the man-in-the-loop effects except as a result of the 'vertical integration' process discussed later.

SE for Force Structures and Defence Policy Analysis

Vertical integration must continue to higher levels still, if the full benefit of SE is to be obtained. Although it is not envisaged that simulators would play a direct role in this high level use, it is worth considering how it operates in order to complete the picture. In this mode SE can address high level questions regarding strategies and the balance of forces against an overall commitment. Fundamentals such as doctrine can also be investigated. The users of the SE in this case are at the highest levels of command. They use the SE to experiment with interactions so that the sensitivities emerge and can be understood. New concepts of operation can be tested assuming either new or existing equipment.

Much of the work is done using the SE for operational analysis where conflicts of significant size can be modelled and the interaction of joint forces can be considered. The SE should also be capable of producing cost indicators for specified conflicts.

Whether or not models at this strategic level prove to be reliable depends upon the assumptions upon which they are based as well as Verification, Validation and Accreditation issues (VV & A) discussed later.

In their simplest form, however, these may be little more than computerised battle tables allowing the thoughts of the user to appear graphically. Even so, there is scope for data capture to take place which could possibly be later used to reinforce the assumptions feeding into other levels of modelling.

SE for Equipment Acquisition and Evolution

The same core processes are used for acquisition or evolution of a weapon system capability as for the training application. Fig 3 shows that instead of concentrating on training procedures and analysis, the measured outputs are concerned with weapon system capability. But the primary difference in this use of SE is that the simulations must be able to accept changes or re-definitions rapidly and accurately in order to allow the options to be analysed for effectiveness.

This is shown by the 'Design Definition' input which may well have many iterations during the assessment of a product. In this way the SE can be used to rapidly converge on a defence solution to meet the given requirements.

Fig 3 simplifies the process by showing a single function which derives costs, timescales and life cycle support implications from the design definition. In reality this is a substantial, industrially based part of the process which runs in parallel with the vehicle or system performance assessments taking place on the simulators. By this means, not only is system effectiveness being addressed but also cost effectiveness, probably the parameter of greatest importance to the SE users.

FLIGHT SIMULATION WITHIN SE

Earlier discussions have indicated the roles of SE in which 'traditional' simulation including Flight Simulators may play a direct part. Not surprisingly, these are the same roles which they currently play but as isolated activities. Considering the roles as part of the SE process does, however, raise several major integration issues. These integration challenges which are discussed below will need to be resolved before flight simulation can play its full role in SE.

Networking Technology - Horizontal Integration

To many people, simulator networking is synonymous with SE. Previous sections of this paper show that networking is just one of the contributing technologies. Before using networks, the case for it must be carefully considered. Local area networks currently give the most satisfactory solutions but are not always possible. Wide area Networks are set up often because legacy simulators and their operators and users are geographically remote. There have been examples where large numbers of forces have interacted (Ref 2). Most demonstrations take place using the Distributed Interactive Simulation (DIS) protocols defined by IEEE 1278. However, current communications technology will only give the quality of interaction suitable for limited tactical training in large conflicts since each operator is receiving outside world feedback cues restricted by network bandwidth limitations and possibly latency. This resultant loss to fidelity is particularly intrusive for simulations of fast moving vehicles such as fighter aircraft.

For a given set of aircraft manoeuvres, there is a relationship which links the rate of transmission of DIS Protocol Data Units (PDU's) to the size of dead-reckoning thresholds which have been specified. Generally speaking, the smaller the threshold, the more PDU's are produced. At the same time, however, the fidelity with which aircraft is represented within the network is increased accordingly. Thus for a given bandwidth capability on the network, conflicts with smaller numbers of players (e.g. tens) could produce the same network loading as a larger (e.g. hundreds) conflict but at a higher level of interaction fidelity because of the lower dead reckoning thresholds. Interaction fidelity could probably be close to that achieved with local area networks where each new entity state is transmitted as soon as it is generated as long as the number of interacting players is not excessive. The large scale demonstrations regularly taking place in the USA tend to use larger dead-reckoning thresholds in order to avoid excessive network loading. Smoothing algorithms are then included to mask discontinuities but these can really only give the illusion of fidelity. Similarly, if simulators are interacting over large geographical distances, the latency effects will also serve to degrade interactions. Again, predictors can be used with limited success.

Fig 4 attempts to plot the situation qualitatively. AB shows that with locally situated simulators using DIS the fidelity of interaction cues decreases as the dead-reckoning thresholds are changed to allow for network bandwidth. Line CD shows a further worsening in cues if the DIS links are over large distances because of increased latency effects. Today's large DIS exercises in the USA can probably be represented by the point X. There are also many smaller scale networks including those in the UK which probably lie at Y which are aimed more at engineering assessments rather than tactical training and have the opportunity for improved cues.

With the passage of time and an increase in bandwidth becoming available, the lines may well move downwards as indicated by EF which shows a future equivalent of line AB.

In summary, at any given time there will exist network technology which gives certain player interaction fidelity characteristics depending upon how it is loaded. The challenge is to stay within the constraints for the task in hand and the conclusions trying to be drawn. Fig 4 should ideally be used by defining the fidelity and size of conflict required and then checking whether the technology can support it. If this is unachievable then careful iterations of both parameters should be made until it is achievable, always taking care that sufficient fidelity will result.

Irrespective of technology constraints, the important question is always: how large a conflict should be simulated. Clearly for training purposes, large groups of players are claimed to be beneficial.

For engineering assessments, excessively large conflicts may make clear analysis and conclusions difficult. On the other hand, too small a conflict may make for a too benign situation to drive out the important issues. Choosing the scenario to match the purpose is and always will be another challenge.

Verification, Validation and Accreditation (VV & A)

The concept of using models and simulation for defence applications is nothing new. The benefit offered by SE is that this modelling is fully integrated, consistent and more extensive than previous work which tended to be fragmented. All computer models need to be used with caution to ensure that they are appropriate for the purpose. A full understanding of their applicability is essential before they are used. The processes for ensuring this are referred to as VV & A. Verification is the process of ensuring that the computer model is a true representation of what the modeller intended. Validation is the process of ensuring that the model is an adequate representation of the real-world system for the purpose intended. Accreditation is the acknowledgement by an authority that a particular model has been cleared for a particular application.

Concerns about the inappropriate use of models beyond their intended scope are highlighted by the scale of modelling within SE. The effectiveness of a weapon system is an emergent property of its interaction with its environment and other players. In order to have confidence in the emergent properties produced by models of the weapon system and its environment, an authority will need to endorse the VV & A of the individual components of the SE as well as the VV & A of the overall system produced when all the models and the

environment interact. When models may be produced by different sources or be legacy models, the role of SE authority raises VV & A issues on an unprecedented scale.

This issue is further highlighted if the network is being used to evaluate an envisaged system which does not yet exist. Where the system already exists, there is at least a reference with which to compare the simulation.

Playing the devil's advocate, a question which might be asked is: are these the real properties of this particular sensor on this particular platform or just an artifact of mismatched software models communicating over an inadequate network?

Rapid Evaluation of Designs

A whole sector of SE briefly referred to earlier is the ability for a requirement to be converted into a design and then into a performance model in a short timescale. This is essential to allow various options to be assessed. A large portion of the SE concept takes the risk out of the production process by rapidly costing the product and estimating the lead time. It also considers the life cycle costs and logistics issues.

With such a system, there are increased opportunities for more design interactions to take place which should ultimately lead to a better product. Even with the faster iteration period proposed by SE, the high payback during this phase may mean that more time is spent in this activity than currently.

Because there may be many options to be assessed by flight simulation, a process must exist to take the design definition and convert it into a simulation reliably and quickly with the appropriate traceability to ensure configuration control. Take for example a new flight control system or cockpit display format. Traditionally, there have been significant delays in transferring these to training simulators and plenty of opportunity for mistakes to be introduced. The SE can only function effectively if the implementation process is rapid and rigorous using an appropriate quality management system. There are a number of methods for achieving this for avionic systems under development within industry at the moment. This capability must be extended to cover all aspects of the weapon system through the use of high-level languages, autocode generators, computer networks, data standards and so on if real-time simulation is not to become a weak link.

Vertical Integration

Higher level wargames often deal with large conflicts primarily to allow such parameters as attrition rates to be calculated by repeated runs of a scenario with weapon system performance tolerances included using Monte-Carlo methods. The same high level models could be used for training commanders in decision making. The assumptions upon which the players' behaviour is based must come from analysis and/or manned simulations of smaller subsets of the conflict. Feeding these assumptions into the wargames from the manned simulators is one example of vertical integration. The process already takes place to an extent within industry and the research establishments. The data can consist of anything from lookup tables to transfer function equations which represents equipment or operator behaviour under certain conditions.

Strengthening and formalising the process by which upward integration takes place will further strengthen the role of both the simulators and wargames in the SE.

A case can be argued for validating the wargame and its data assumptions by cross checking its behaviour with an identical conflict but with one or more of the entities being coupled in real-time to manned simulators. If the same kind of results are obtained then it should confirm that the upward integration process was valid. The wargame could then be confidently used without the need for on-line manned simulators.

Another benefit of real time vertical integration between manned simulators and wargames could be the higher levels of realism which the simulator operator could experience since he would become part of a realistic sized conflict. However it must be remembered that for many training or evaluation purposes, small conflicts are perfectly adequate (for example initial flying training).

Some wargames, particularly those representing land battles, rely on aggregation and de-aggregation to represent large forces. Attempting to couple a manned simulator into such an aggregation of entities presents a further set of problems.

The relatively low numbers of aircraft used in conflicts compared with the numbers of land vehicles probably means that flight simulators can avoid this particular problem.

CONCLUSIONS

The fully integrated SE is a long term vision. Many of the components are here now. Integration can begin. When the tool is in place, it will help all those involved in the defence process to be more effective. What it will not do is to replace intellectual power. We will need the same amount of thought hours to reach the same decisions. But the work supporting those decisions should be made easier with a higher degree of confidence and more visibility of the outcome.

There will, of course, be things you can do in the SE which you couldn't do before such as the large conflict simulations. These are part of the SE process, however, not the whole. Flight Simulation as we know it today has the challenge of adapting to take its place in the SE. Most of the issues centre around integration whether it be horizontal networking, vertical integration or integration with design definitions. Pervading the whole process are the V,V and A issues and the organisation to support them.

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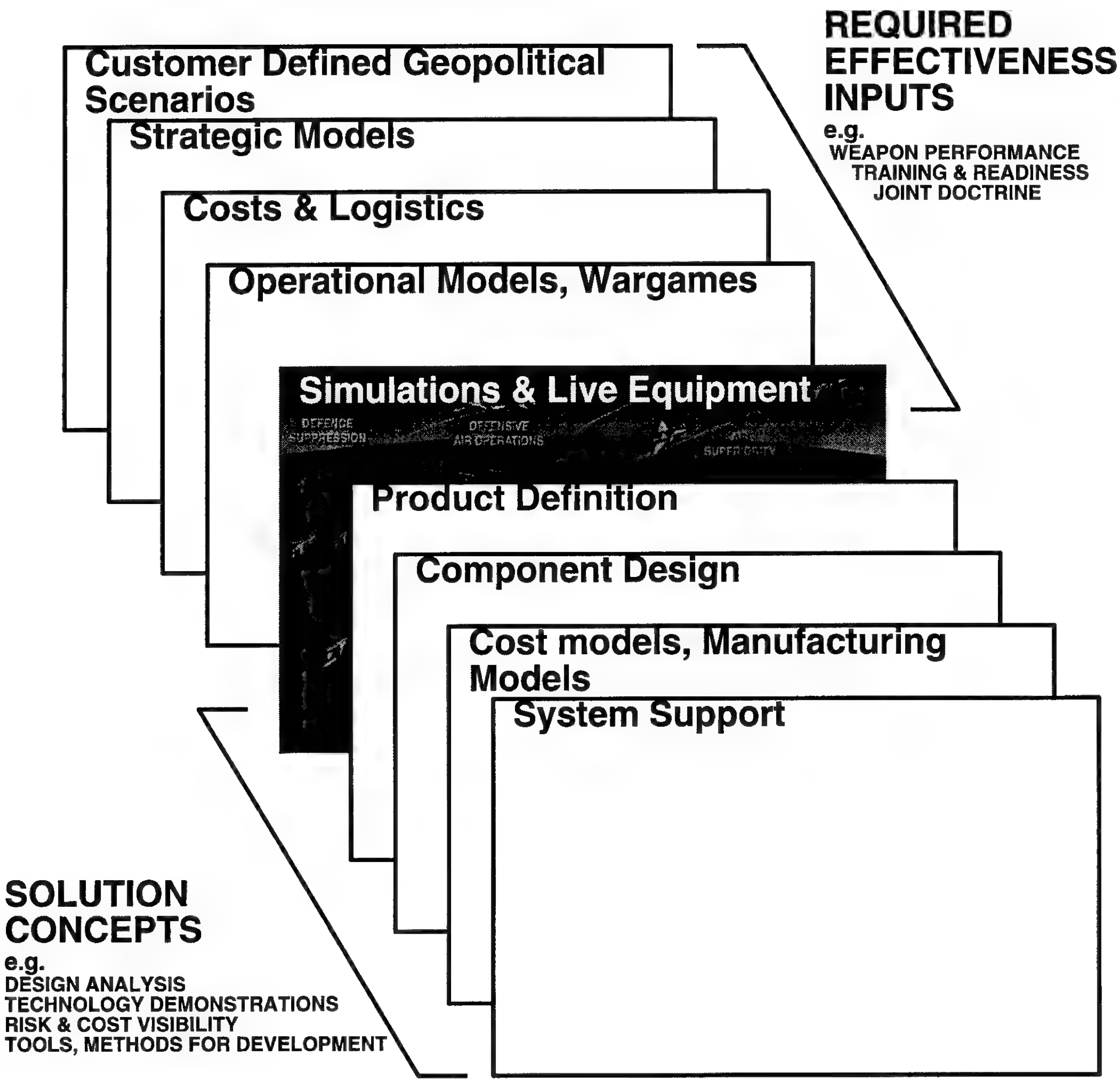

FIG 1. THE SYNTHETIC ENVIRONMENT HIERARCHY

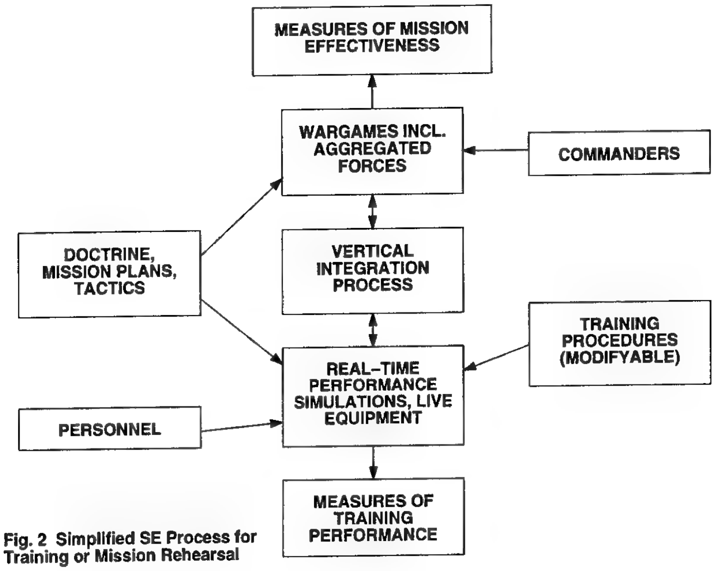

Fig. 2 Simplified SE Process for Training or Mission Rehearsal

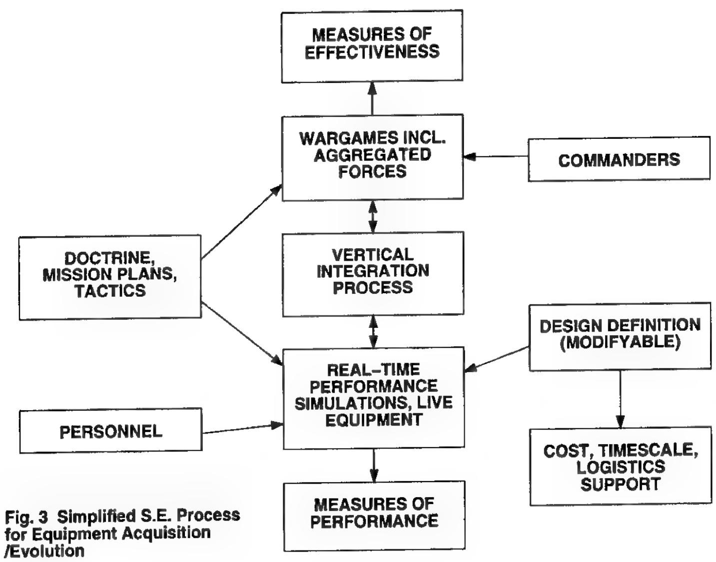

Fig. 3 Simplified S.E. Process for Equipment Acquisition /Evolution

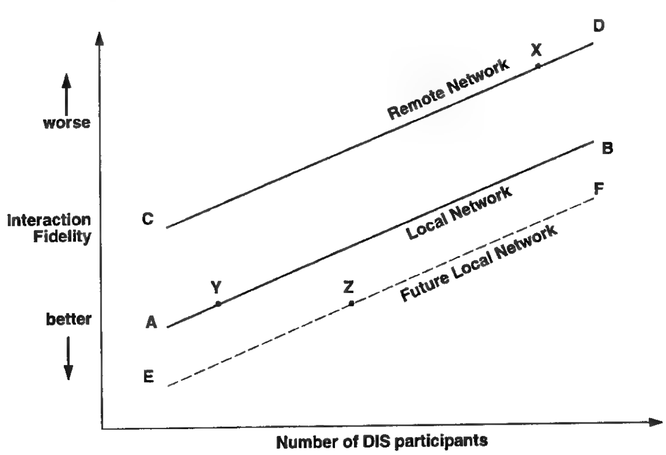

Fig. 4 Network characteristics

Estimating The Training Effectiveness of Interactive Air Combat Simulation

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SUMMARY

This paper is concerned with the general problem of measuring the value of simulation for combat mission training. There are a number of engineering efforts currently attempting to develop multi-player, virtual simulations that will allow soldiers, sailors, and pilots to interact with one another in a synthetic battlefield for combat mission training. This paper will briefly discuss the continuation training environment that simulation must effectively complement and the various approaches for obtaining training effectiveness data for estimating the training payoff of these efforts. It will then summarize the results of recent efforts conducted by the Armstrong Laboratory to assess the value of combat mission simulation for continuation training of pilots. Although the results of these studies indicate high user acceptance for simulation and improved performance during the course of simulator-based training, transfer of training data has yet to be obtained.

1. INTRODUCTION

The United States Air Force (USAF) spends a great deal of money to develop and maintain the combat proficiency of its pilots. Most of this combat-oriented training is conducted at the operational unit as part of its continuation training program. The basic instructional media for continuation training are the aircraft, the environment in which it operates, and the post-mission debrief. Together they provide an on-the-job training environment built around the opportunities for in-flight training. In-flight training opportunities, however, are limited by many factors (1). These factors include: peacetime training rules, resource limitations, technical constraints, and security restrictions. Each of these factors places restrictions or imposes unnatural constraints on training. Peacetime training rules impose altitude and weather restrictions, limit use of communications jamming, permit limited weapons firings, and require a minimum separation between aircraft. Resource limitations restrict the number of aircraft available for training, the number of flying hours available, and the size of the training ranges. Technical constraints limit the use of electronic warfare systems, prevent practice against an integrated air defense system, and limit the measurement of combat performance. Security restrictions prevent full employment of classified systems, communications, and tactics. These factors combine to limit the opportunities for training combat tasks at both individual and team levels.

In developing its multiship simulation program, the Armstrong Laboratory's Aircrew Training Research Division, in cooperation with the Air Combat Command, surveyed over 300 mission ready (MR) pilots and air weapons controllers (AWCs) to identify continuation training needs (2,3). Responses to these surveys were surprisingly similar no matter the respondent's experience level, unit, or weapon system. The consensus is that it is difficult to train the pilot and AWC to make full use of the weapon system as part of a combat team. Table 1 shows the combat training areas most frequently mentioned as needing improvement.

Table 1. Mission Activities Most Frequently Mentioned As Requiring Additional Training

Multibogey, four or more
All-aspect defense
Reaction to surface-to-air missiles
Dissimilar air combat tactics
Four-ship tactics
Reaction to air interceptors
Employment of electronic countermeasures
Chaff/flares employment

These mission areas involve the very tasks for which in-flight training is most likely to be constrained by the factors mentioned above. If anything, the negative impacts of these factors on training will increase in the future. Therefore, we must develop other training approaches that will maintain the readiness of our combat air forces. Simulation is one such approach (4). In particular, distributed interactive simulation seems especially promising since it offers the potential interactivity that characterizes the combat environment.

Because of the high cost of flight simulators and the potential consequences of inadequate training, one would assume there is an extensive research base establishing the value of training combat tasks in simulators. It is not unreasonable to ask questions such as: Was the simulator training effective? Can it be improved? How frequently is it needed? Is simulation

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worth the costs? All of these questions reflect the need to evaluate the potential benefits of distributed simulation for combat-oriented training.

2. MEASURING TRAINING BENEFITS

An immediate question becomes exactly how to evaluate the benefits of simulation-based training as a means of improving combat mission performance. Bell and Waag (5) have proposed a five-stage sequential model which is briefly summarized below.

Stage 1. Utility Evaluation. The objectives of the initial stage are to (a) evaluate the accuracy or fidelity of the simulation environment; and (b) to gather opinions from users concerning the potential value of the simulation for specific training applications.

Stage 2. Performance Improvement. The objective of the second stage of the evaluation is to determine the extent to which performance improves during the course of training within the simulation environment. The major challenge during this stage of the evaluation is to ensure that there is a proper means of establishing that performance has indeed improved as a result of the training. This requires the development of mission scenarios that are flown before and after the training that are similar to but not identical to missions flown during training. It also requires the development and use of measures whereby improvements in performance can be meaningfully reflected.

Stage 3. Transfer to Alternative Simulation Environment. The question of generalizability now is raised--does training transfer to another environment? While the acid test is usually considered to be transfer to the air, it is our view that a more logical intermediate step involves demonstrating transfer to other simulation environments. Recall that one of the primary justifications for multiplayer air combat simulation is the ability to practice certain events under conditions that are generally not available in peacetime training environments. Because of safety restrictions, security considerations, rules of engagement, etc., peacetime exercises will always be limited in terms of their situational fidelity. For this reason, it is essential that transfer be demonstrated to another simulation environment in which a wartime environment can be created.

Stage 4. Transfer to Flight Environment. If positive transfer to a simulated wartime environment has been shown, the next stage is to show transfer to the air. Unfortunately, such a transfer test is limited by the large number of peacetime restrictions that characterize current flight operations. For this reason, a smaller sample of combat tasks would most likely have to be selected for evaluation. To whatever extent possible, the transfer test should represent a highly controlled flight environment wherein performance data can be gathered easily.

Stage 5. Extrapolation to Combat Environment. The last stage of the evaluation process attempts to answer the question of the military value of training. As might be expected, an empirical approach is not amenable for this question. Rather, a modeling approach is recommended as a means of extrapolating from simulator-based training to a combat environment. An example of such an approach is provided by Deitchman (6) in an attempt to project the impact of training into a central European type of wartime scenario. In that case, arbitrary estimates were used to represent the potential impacts of training. However, data from a systematic evaluation program, which recorded performance as a function of training, could easily be substituted into constructive models at the engagement level and the results fed into the higher level mission and campaign models. For example, training effectiveness data might show that survival is increased by an average of 25% as a result of simulator-based training. Using constructive simulations, the relative impact of such changes could be assessed in operational terms.

3. F-15 ADVANCED AIR COMBAT SIMULATION

In concert with this model, the Armstrong Laboratory has been gathering data over the past few years attempting to establish the value of simulation for air combat training. In 1988, a program was initiated with the Tactical Air Command (now Air Combat Command) to evaluate multiship air combat training using commercially available contractor facilities. In all, two utility evaluations and one simulator performance improvement study were conducted as part of this project.

These efforts used the McDonnell Aircraft Simulation facility in St. Louis, Missouri. This simulation system was designed to support engineering development. Its design and equipment typify the full mission simulator facilities developed by aircraft manufacturers in the late 1980s. Figure 1 shows the principle components of this system. Each F-15C cockpit was located in a 40-ft diameter dome which provided the pilot with a nearly full field of view. Each simulator had high fidelity aerodynamic, engine, avionics, communication, sensor, and weapon simulations. Other components included additional aircraft (either digital or manned), digitally controlled surface-to-air-threats, exercise control, debrief, and data record. A more detailed description of the basic simulation system is available (7).

Utility Evaluations. Two utility evaluations were conducted. In the first evaluation (8), 42 mission-ready F-15 pilots and 16 AWCs received four days of training. The training unit was the team comprised of two pilots (lead/wingman) plus the AWC. This team flew a variety of combat missions against an opposing force comprised of four to eight adversaries plus the adversary AWC.

Upon completion of training, pilots rated the value of both their "unit training" and the "simulation training" for 41 air-to-air tasks. The pilots felt that simulator training was much better than their current unit training for many air combat tasks

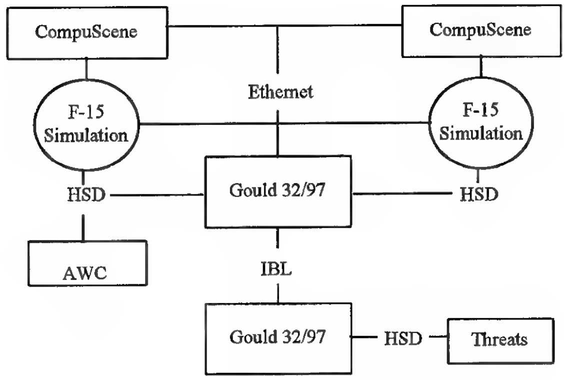

Figure 1. McDonnell Douglas Simulation Facility

including multibogey, chaff and flares employment, all-aspect defense, use of electronic countermeasures and counter-countermeasures, communications jamming, and work with the AWC. These tasks were also rated high in "need for additional training" prior to the start of simulator training. On the other hand, tasks such as air combat maneuvering (ACM), visual lookout, gun employment, and basic fighter maneuvering (BFM) were rated as better trained in their in-flight continuation training program than in the simulation. Air weapons controllers, however, rated all tasks as better trained in the simulation environment. Open-ended opinion data were also gathered, the results being quite positive toward the training.

A second evaluation, was conducted using the same procedure but with a larger sample of pilots and AWCs (3). This evaluation produced essentially the same results. Based on the high user acceptance demonstrated during these utility evaluations, Air Combat Command continued this program under its own sponsorship.

Performance Improvement. In the third study, again using the same facility, in-simulator learning was also shown, in addition to positive user opinion. Subjects consisted of 16 teams, each team being made up of two pilots and an AWC. Each of the elements flew controlled offensive and defensive scenarios "before" and "after" three days of intensive simulation training. Digital data as well as videotapes of displays used for replay and debriefing purposes were archived for later analysis.

Preliminary analyses reveals that post-training mission performance is significantly higher than pretraining performance. Figure 2 shows the mean value of several pre- and post-training mission performance indicators for defensive counterair missions. The data clearly indicate that the probability of mission success (i.e., no enemy strikers to target) and F-15 survival increased during the course of the simulator training ($p < .05$). In addition, weighted exchange ratios, reflecting the efficiency of mission accomplishment, also increased as a function of training ($p < .05$).

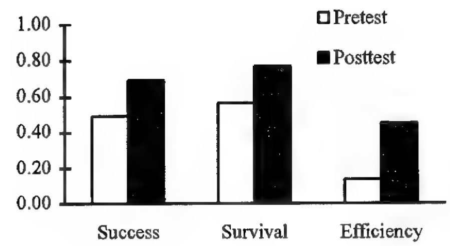

Figure 2. Comparison of Pre/Post Test Performance

4. F-15 SITUATION AWARENESS STUDY

In 1991, the US Air Force Chief of Staff posed a series of questions concerning situation awareness (SA). First of all, what is SA? Can it be objectively measured? Is SA learned or does it represent a basic ability or characteristic that some pilots have and others do not? From a research standpoint, these questions translate into issues of measurement, selection, and training. The Armstrong Laboratory was subsequently tasked with providing research answers to these questions. A research investigation was initiated that had three goals: first, to develop and validate tools for reliably measuring SA; second, to identify basic cognitive and psychomotor abilities that are associated with pilots judged to have good SA; and third, to determine if SA can be learned, and if so, to identify areas where cost-effective training tools might be developed and employed. An overview of the investigation can be found in McMillan, Bushman, and Judge (9).

The general approach was to first develop criterion measures of SA based upon performance ratings collected within an operational flying environment. The results of this part of the study can be found in Waag and Houck (10). These measures were necessary for two reasons. First, they would serve as criterion measures against which to validate a battery of basic ability tests considered relevant to SA, thereby addressing the question of basic human abilities. The results of this part of the study can be found in Carretta and Ree (11). Second, these measures would serve as a means of selecting a sample of pilots who would participate in a simulation phase of the effort. During that phase, simulated air combat mission scenarios were developed for assessing SA and objective measures of performance gathered in an attempt to determine those characteristics that distinguish pilots with good SA. These data would be used to identify areas where training tools might be developed. We now summarize the results of the third phase of the program, namely the use of simulation as a tool for measuring and training SA. The complete findings are presented in Waag, Houck, Greschke and Raspotnik (12).

Method. A total of 40 MR F-15 pilots, who were flight lead-qualified served as subjects. An additional 23 MR F-15 pilots served as wingmen throughout the data collection. The simulated combat missions were flown using the Armstrong

Laboratory's multiship simulation facility (MULTIRAD) located at Williams AFB (WAFB), AZ. The major components of the simulation system are shown in Figure 3. These components represent independent subsystems operating as part of a secure distributed simulation network. This local area network was connected to the air weapons controller simulator (AESOP) at Brooks Air Force Base (BAFB), TX by a dedicated T-1 telephone line. Additional details concerning the basic simulation architecture and components are available (13,14,15).

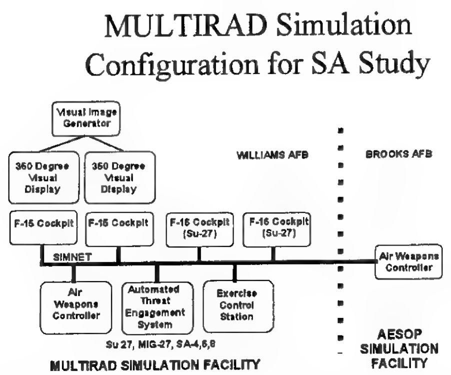

Figure 3. Armstrong Laboratory Simulation Facility

The manned flight simulators consisted of two F-15C simulators and two F-16 simulators. The F-15C simulators had high fidelity aerodynamic, engine, avionics, radio, sensor, and weapons simulations. Each F-15C simulator was equipped with an out-the-window visual display system covering approximately 360 deg horizontal by 200 deg vertical. The external visual scene was created using computer-generated imagery. The lower fidelity, manned F-16 simulators played the role of enemy aircraft in conjunction with computer-controlled adversaries. The visual and electronic signatures of these F-16 simulators were modified so that they appeared as the appropriate threat aircraft. Each F-16 simulator was equipped with a single channel of out-the-window visual imagery covering approximately 45 deg horizontal by 45 deg vertical. A manned AWC provided the F-15C pilots with appropriate threat information and warnings. Depending upon the availability of qualified AWCs and equipment status, the AWC was either located at WAFB or BAFB. In either case, the AWC had a realistic simulation of the appropriate AWC console and communicated with the F-15C pilots by radio.

The primary approach taken toward the measurement of SA was through scenario manipulation and observation of subsequent performance. A week-long SA "evaluation" exercise was constructed that consisted of 9 sorties with 4 engagements per sortie. Sorties were arranged in a building block manner. Over the week, engagements increased in complexity in terms of numbers of adversaries, enemy tactics, lethality of ground threats, AWC support, etc.

The same two subject-matter experts (SMEs) were used throughout the year-long data collection effort. Upon completion of the mission, they discussed each engagement, and completed a consensus performance rating scale consisting of the 24 behavioral indicators of SA related to F-15 mission performance. A variety of other data were also gathered and archived, including mission events and outcomes, digital data passed over the network, videos used for debriefing, eye movement data recorded on the last mission, and finally, "critiques" of the simulation and opinions regarding its potential for training. Two types of user opinion data were gathered. First, pilots rated the training benefit for various pilot experience levels. And second, pilots completed an open-ended questionnaire pertaining to the overall value of the simulation and how it might best be used.

Findings. The results of the ratings of potential training benefits are provided in Figure 4. These data clearly indicate that positive opinions were expressed by the study participants on the value of this type of simulation for training. The potential training was considered beneficial for all levels of qualification. It is of interest to note that training was considered highly beneficial for four-ship flight leads, despite the fact that the MULTIRAD simulation facility provided training for only a flight lead and wingman. As expected, higher benefit ratings were given to pilots upgrading into a given qualification level.

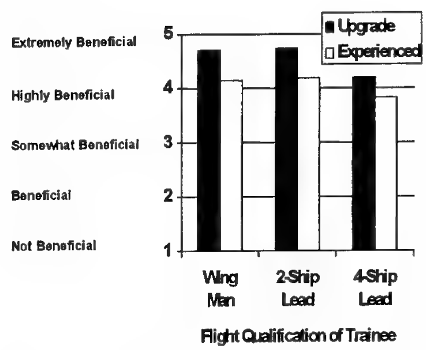

Figure 4. Rated Benefits of Simulation Training

Opinions expressed in the open-ended questionnaire were also quite positive. Although qualitative, they provide additional insight into the potential focus of training using multiship simulation and how it might be employed. In particular, mention was made of using such training as a means of enhancing both situation assessment and decision-making skills. It was also frequently noted that there was tremendous value in learning flight leadership and resource management skills. In terms of the location of such simulation, the overwhelming consensus was that they would be of most value within the operational units. This was not too surprising since each unit now has the operational version of the cockpits used in the present investigation. However, they are stand-alone and non-visual, and as such their training capability is fairly

limited. In contrast, the networking of such devices within a realistic combat environment increases the potential greatly. The bottom line from the utility data is that the participants considered multiship simulation as a tool with high training potential.

It should be pointed out that it was never the intent, at the outset of the study, to demonstrate performance improvements. It must be emphasized that the sole purpose was to develop a set of simulation scenarios that could be used to assess SA within a combat environment. As such, normal training interventions were not permitted. For example, during the debrief, pilots were permitted to only view their own in-cockpit displays and not the planned view display. Moreover, the two SMEs were not permitted to provide any type of feedback to the pilots regarding their performance. However, data from the ninth mission did permit some comparison since identical scenarios had been flown earlier in the week. The ninth mission was designated the "eye track" mission in which eye movement data were recorded.

Two scenarios, a 2 V 2 defensive counterair (DCA) mission and a 2 V 4 offensive counterair (OCA) mission, were flown during the middle of the week and then again on the last mission. A comparison of performance is presented in Figure 5. In both cases, performance on the last mission was improved. However, only the 2 V 2 DCA mission was found to be statistically significant. When such data are coupled with the very strong pilot opinions that they had received valuable training, it seems reasonably safe to conclude that learning had occurred over the week.

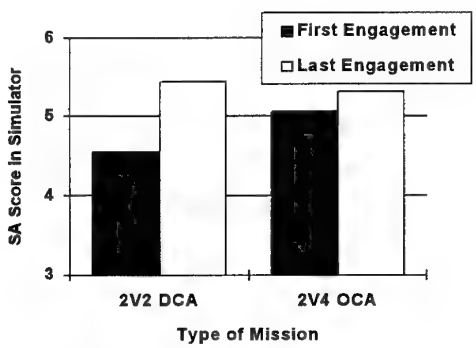

Figure 5. Effects of Practice on Observer SA Ratings

5. MULTISERVICE DISTRIBUTED TRAINING TESTBED

The Armstrong Laboratory is currently working with the Army Research Institute and the Naval Air Warfare Center to develop a training testbed that can be used to assess the value of Distributed Interactive Simulation for multiservice training. This effort, initially sponsored by the Defense Modeling and Simulation Office, links service-developed training systems together to create a Multiservice Distributed Training Testbed (MDT2). MDT2 provides a common, virtual environment that is being used to support training research involving collective tasks.

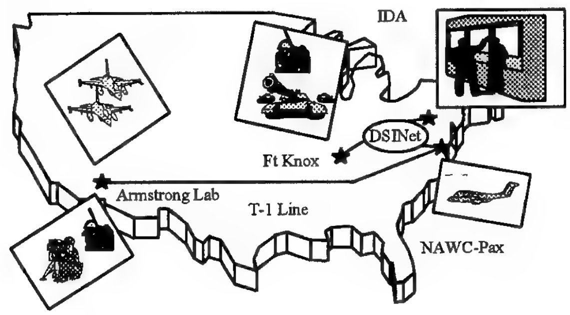

Figure 6. Multiservice Distributed Training Testbed

Currently, MDT2 is focusing on the planning and execution of close air support (CAS) at the engagement level. The goal is to establish a virtual training environment. The participants in this virtual training environment will be soldiers, marines, and pilots executing their unique combat tasks in virtual simulators at their individual service training sites. This environment will allow collective training to occur which involves both unit and task force components.

The initial training utility evaluations of MDT2 were conducted in May of 1994 and February of 1995. For the February evaluation, four sites were interconnected using Distributed Interactive Simulation Protocol 2.0, version 3. These sites were the Institute for Defense Analysis in Alexandria, Virginia; Mounted Warfare Testbed at Ft. Knox, Kentucky; the Manned Flight Simulation Facility at Patuxent River, Maryland; and the Armstrong Laboratory at Mesa, Arizona. This simulation network is illustrated in Figure 6, while information regarding each of the sites is summarized in Table 2.

Table 2. Simulation Testbed Components

Location	Simulators	Role
Armstrong Laboratory	2 F-16	Close Air Support
	1 Laser Designator	Scout and Target Designation
Naval Air Warfare Center	OV-10	Forward Air Control
Mounted Warfare Testbed	M-1A1 M-2	Ground Maneuver Battalion Tactical Operations Center
Institute for Defense Analysis	None	Stealth Display Data Record

The results of this training effectiveness evaluation indicated that mission-ready fighter pilots, airborne forward air controllers, and ground combatants felt that the simulation

provided significant training benefits. In addition, trained observers and subject-matter experts monitored that performance of selected mission tasks throughout the training period. The data indicated that mission performance for each of the components, air and ground, increased over the four days of simulated combat. The high user acceptance and increase in performance are most likely due to the unique ability that MDT2 provides for planning, execution, and review of close air support as an integral part of the ground commander's battle plan.

6. DISCUSSION

The results obtained from these efforts provide strong user belief in the value of interactive air combat simulation. From the user's perspective, the data are very clear regarding the potential value of such simulation for training. Users consistently report that such simulations are an enhancement to their current mission training. Although such subjective evidence is often considered suspect from a scientific perspective, it is nevertheless an absolute prerequisite for effective training. Unless there is user acceptance, the resulting training will be of marginal value regardless of the device's inherent potential.

In addition to the opinion data, there is evidence that performance did improve within the simulation environment. Performance improvements were demonstrated in the F-15 Advanced Air Combat Simulation, the F-15 Situation Awareness Study, and the Multiservice Distributed Training Testbed. These data, combined with the fact that the study participants expressed opinions to the effect that their proficiency had improved, leave little doubt that learning had occurred.

Although the data clearly indicate that the end user expresses very positive opinions toward the value of multiship simulation and that learning occurs, there still remains the issue of transfer of training. Does such training transfer to other simulation environments (Stage 3 of the Evaluation Model) and does it transfer to the real world (Stage 4 of the Evaluation Model)? The data gathered in this study do not bear upon these issues.

The question becomes, "are transfer of training data needed?" While no one would argue the desirability of having such data, there are practical issues which seriously question the advisability of conducting such studies. Lack of experimental control, insufficient sample sizes, insufficient training time in the simulator, insufficient time for evaluating transfer in the air, insensitive measures, etc. are problems that plague the conduct of any transfer of training evaluation (16). In fact, one can argue that it is virtually impossible to conduct a well-controlled transfer test within an operational military environment.

This inability to adequately control such evaluations perhaps has its greatest impact on the interpretation of findings, particularly when these findings show no transfer effects or fairly small transfer effects. The empirically obtained outcome for any transfer of training experiment is one of three possible outcomes; positive transfer, no transfer, or negative transfer. Similarly, the true effect of training is one of the same three possibilities. The problem is to infer the true state from the obtained outcome. This inferential process works quite well when statistically significant outcomes confirm expectations. Unfortunately, the inference process does not work as easily when little or no transfer is obtained as a result of training. Now the investigator must decide between two possibilities. Indeed, the training may have little of no effect on performance. Or, the effects may be much larger, but because of methodological problems inherent in conducting transfer of training experiments, they are masked. Although we do not know the true effects of training, we generally attempt to "explain away" any lack of positive effects and attribute it to these "methodological problems," especially if there are other data such as expert opinion that suggest the training to be beneficial.

A good case in point is a study by Pohlmann and Reed (17) that failed to show positive transfer effects for ACM training in the Simulator for Air-to-Air Combat (SAAC). Do we believe that simulator training does not improve air-to-air performance? Probably not, since we have other evidence suggesting the training to be beneficial. This evidence includes positive end-of-course opinions suggesting training in the SAAC to be some of the best air-to-air training pilots had ever received, in-simulator performance improvements (18), and positive transfer of training in another experiment (19). The study failing to demonstrate positive transfer had one potentially serious limitation in that instructor ratings were used as a measure of performance. Such measures have been shown to be quite insensitive in other air combat domains. For example, a study by Gray and Fuller (20) which demonstrated significant transfer of training in terms of bombing accuracy, also used instructor ratings of performance in the air. Interestingly enough, the rating data showed no effects of simulator pretraining despite large differences in objective measures of weapons delivery. So it seems at least plausible that the failure to show any effect in the Pohlmann and Reed (17) study may have been due largely to the measures that were used. For this reason and the fact that we have other evidence suggesting the training to be valuable, we can make the case to simply "dismiss" these findings.

At this point, we have a paradox emerging. On the one hand, we have made the argument that the transfer of training evaluation is the only <u>sufficient</u> test for establishing training effectiveness. On the other hand, we have also shown that we tend to dismiss those studies failing to demonstrate positive transfer when we have other data, which is usually expert opinion, suggesting the training to be effective. In such instances we attribute the lack of positive transfer effects to one or more of those "methodological problems" which always exist in the conduct of such evaluations within an operational military training environment. If we are willing to explain

away our inability to demonstrate training effectiveness, the question becomes, "why conduct the transfer evaluation?"

Since there is currently no definitive data, the question of training benefits of interactive air combat simulation is largely answered by ones' personal view of simulation and one's willingness to generalize from previous investigations of transfer in other domains. For the "believer," including the authors of this paper, the evidence to date is strong enough to warrant the conclusion that training will be effective. In fact, given the previous transfer of training research that has already been conducted (5,16) there is little reason to suspect that such training within a multiship simulation environment would not have a positive effect upon subsequent performance in the air. Consequently, there is no compelling reason to conduct transfer of training studies within the air combat environment. However, for the "skeptic," no definitive evidence has been presented and the question remains unanswered.

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14. Abstract

Effective Flight Simulation is an important capability for NATO nations, and it will become even more important in the face of reductions in defence budgets. This symposium reviewed the state of the art in flight simulation, in order to identify weaknesses where additional research and development are needed. Presentations dealt with simulation used for engineering and for training, both on the ground and in-flight.

Session topics were:

— Visual and Motion Cueing and Requirements;
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— Simulation in Design and Development – Rotorcraft;
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The keynote address introduced the symposium, clearly establishing the importance of the topic and its relevance to NATO's requirements.
A Technical Evaluation Report is also included.

Copies of papers presented at the Flight Vehicle Integration Panel Symposium held in Braunschweig, Germany, 22-25 May 1995.

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